TAPPING INTO NATURE

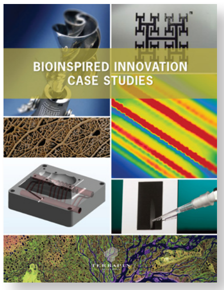
THE FUTURE OF ENERGY, INNOVATION, AND BUSINESS

TERRAPIN

BRIGHT GREEN

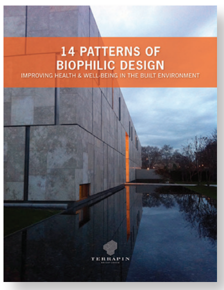
OTHER PUBLICATIONS BY TERRAPIN

These publications and others can be accessed for FREE on
Terrapin Bright Green's website: www.terrapinbg.com/publications



Bioinspired Innovation Case Studies

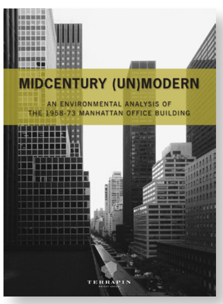
Building on our *Tapping into Nature* report, Terrapin is creating a series of bioinspired innovation case studies based on our past projects. The case studies review technologies that were developed using the guidance of Terrapin's bioinspired innovation team and network of experts. The bioinspired solutions often overcome challenges present in a wide array of industries. These case studies are meant to help companies, research teams, and organizations better understand how bioinspired innovation can be successfully implemented to tackle industrial challenges, minimize risk, maximize profits, and reduce environmental impact.



14 Patterns of Biophilic Design

Improving Health and Well-Being in the Built Environment

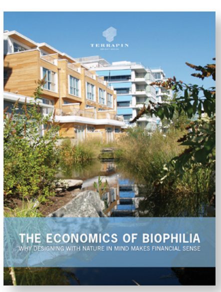
Biophilic design can reduce stress, enhance creativity and clarity of thought, improve our well-being and expedite healing; as the world population continues to urbanize, these qualities are ever more important. Theorists, research scientists, and design practitioners have been working for decades to define aspects of nature that most impact our satisfaction with the built environment. 14 Patterns of Biophilic Design articulates the relationships between nature, human biology and the design of the built environment so that we may experience the human benefits of biophilia in our design applications. This paper moves from research on biophilic responses to design application as a way to effectively enhance health and well-being for individuals and society.



Midcentury (Un)Modern

An Environmental Analysis of the 1958-73 Manhattan Office Building

This paper compares the relative opportunities of retrofit vs. replacement strategies for the tens of million square feet of commercial office buildings built in Manhattan from the 1950s through 1970s, most of which were built with single-glazed curtain walls – designed to the standards and ideals of their day. Today we are acutely aware of the demands buildings place on precious resources like energy and water. This segment of the city's building stock needs to be overhauled; the question is how best to approach the task. Based on in-depth analysis of a representative early curtain wall building, this paper explores three main conclusions: 1) Maintain, with an intermediate stage of energy savings; 2) Retrofit, theoretically achieving 40% lower energy use; and 3) Replace, could a high-performance replacement building increase occupancy while actually reducing total energy use? And, what are the environmental burdens?



The Economics of Biophilia

Why Designing with Nature in Mind Makes Financial Sense

This paper makes the business case for incorporating biophilia into the places where we live and work. We share several examples of small investments in biophilic design that lead to very healthy returns: Integrating views to nature into an office space can save over $2,000 per employee per year in office costs; and providing patients with views to nature could save over $93 million annually in national healthcare costs. These examples, based on scientific research, serve to demonstrate the financial potential for the large-scale deployment of biophilic design in hospitals – speeding up patient healing; in offices – boosting productivity; in schools – improving test scores; and in retail outlets – boosting sales.
In 2014, *The Economics of Biophilia* was recognized with the Environmental Design Research Association's 2014 Achievement Award.

COVER IMAGE

Similar to systems and structures seen in nature, humanity's networks of lights, roads, and cities convey energy, materials, and information. Intentionally mimicking these natural systems offers a path to a prosperous future for our society.

“I’m not trying to imitate nature; I’m trying to find the principles she’s using.”

R. Buckminster Fuller, 1972
Buckminster Fuller to Children of Earth

ACKNOWLEDGEMENTS

The authors would like to thank the New York State Energy Research and Development Authority, or NYSERDA, for sponsoring this document. We owe Miriam Pye and Dana Levy a large debt of gratitude for championing this work. The authors would also like to thank the Review Committee for their valuable contributions and the Affari Project for developing the online version of this document. Additionally, we are grateful to Joe Coussan and Natalie Mault Mead for their editorial assistance. The opinions and conclusions in this report are solely those of the authors and do not necessarily reflect the views of NYSERDA, the reviewers, or editors.

CO-AUTHORS

Cas Smith	Terrapin Bright Green
Allison Bernett	Terrapin Bright Green
Erika Hanson	Terrapin Bright Green
Chris Garvin	Managing Partner, Terrapin Bright Green

REVIEW COMMITTEE

Nathaniel Cady	Associate Professor, SUNY Polytechnic Institute
Mark Dorfman	Biomimicry 3.8
Jamie Dwyer	Biomimicry 3.8
Paolo Gaudiano	CEO, Infomous, Inc.
Jay Harman	CEO, PAX Scientific
Tim Hoffman	Managing Director, Watts Capital/NYSERDA EIR
Mathias Kolle	Assistant Professor, MIT
Sandra Meier	Senior Project Manager, NYSERDA
Pat Sapinsley	CEO, Watt Not LLC/Build Efficiently LLC
Abraham Stroock	Associate Professor, Cornell University
Jiandi Wan	Assistant Professor, RIT

CONTRIBUTORS

Cathy Gallagher	Fermanian Business & Economic Institute
Dieter Mauerman	Fermanian Business & Economic Institute
Lynn Reaser	Fermanian Business & Economic Institute
William Browning	Terrapin Bright Green
Catie Ryan	Terrapin Bright Green
Chris Starkey	Terrapin Bright Green
Jonce Walker	Terrapin Bright Green

TERRAPIN
BRIGHT GREEN

Terrapin Bright Green LLC
New York NY | Washington DC

www.terrapinbrightgreen.com
biomimicry@terrapinbg.com

@TerrapinBG | @NY_Biomimicry
#TapNature

ABOUT TERRAPIN

Terrapin Bright Green is an environmental consulting and strategic planning firm committed to improving the human environment through high performance development, policy, and related research, in order to elevate conversations and help clients break new ground in thinking creatively about environmental opportunities. Since 2006, our firm and our network of specialists have worked to shape the outcome of large-scale planning and design projects around the world. Terrapin has offices in New York City and Washington, DC, and works with private companies, public institutions, and government agencies on a variety of project types. Visit us at www.terrapinbrightgreen.com.

COPYRIGHT AND COMMERCIAL USE

Suggested Reference: C.A. Smith, A. Bernett, E. Hanson, C. Garvin, *Tapping into Nature*, Terrapin Bright Green LLC, 2015.

NOTICE

This report was prepared by Terrapin Bright Green LLC in the course of performing work contracted for and sponsored by NYSERDA. The opinions expressed in this report do not necessarily reflect those of NYSERDA or the State of New York, and reference to any specific product, service, process, or method does not constitute an implied or expressed recommendation or endorsement of it. Further, NYSERDA, the State of New York, and the contractor make no warranties or representations, expressed or implied, as to the fitness for particular purpose or merchantability of any product, apparatus, or service, or the usefulness, completeness, or accuracy of any processes, methods, or other information contained, described, disclosed, or referred to in this report. NYSERDA, the State of New York, and the contractor make no representation that the use of any product, apparatus, process, method, or other information will not infringe privately owned rights and will assume no liability for any loss, injury, or damage resulting from, or occurring in connection with the use of information contained, described, disclosed, or referred to in this report.

TAPPING INTO NATURE

THE FUTURE OF ENERGY, INNOVATION, AND BUSINESS

TABLE OF CONTENTS

ABSTRACT

By tapping into billions of years of research and development, innovative companies are abstracting strategies from the natural world and developing truly transformative technologies. Organisms have flourished on Earth for nearly 4 billion years, continuously adapting to our planet's diverse environments and diffuse energy flows. *Tapping into Nature* explores how pioneering companies are leveraging these adaptations and demonstrates the vast and largely untapped market potential of bioinspired innovation.

In this paper, Terrapin explores nine cross-sector topics and selects natural strategies related to each. The biological strategies represent only a fraction of the designs found in nature. Each section then presents bioinspired products—some of which are Terrapin collaborations—that have been developed by companies using these strategies. All told, this set of strategies and products begins to convey the breadth of innovation in the natural world.

The infographic "Market Readiness of Bioinspired Innovations" on page 8 showcases over 100 examples of bioinspired technologies, ranging from early concepts to profitable commercial products. The broader economic and environmental potential of this rapidly growing field is detailed on page 10 in "Bioinspired Innovation: An Economic Engine." By tracing the path from biology to commercialized technologies, we hope to inspire you to tap into nature at your organization.

INTRODUCTION

Nearly all living things rely on diffuse and transient flows of energy and materials. And yet, life thrives. Organisms are able to procure materials and assemble themselves—essentially constructing "technologies"—using only the resources that are locally available.

Increasingly, innovative companies are looking to the living world for inspiration and direction. Nature provides a rich yet largely unexplored library of technologies that process and manage information, materials, and energy.[1] Abstracting ideas from this catalogue opens the way to technological breakthroughs and profitable innovation that are often unattainable using conventional approaches to product design and development.

"Bioinspired innovation," a term used throughout this paper, encompasses two distinct categories. One of them, *bioutilization*, is the use of organisms or biological materials to fulfill a human need. The other, *biomimicry*, is the abstraction and translation of biological principles into human-made technology; it is also a method of assessing whether a design concept is likely to "create conditions conducive to life."[2] The terms are related yet distinct. Either approach can be implemented in a way that benefits society and the environment.

Bee communication within hives inspired Encycle's Swarm Logic™ systems that cut the peak energy demand of building heating and cooling systems (see Data & Computing).

BLUEPRINTS FOR INNOVATION

Life can be thought of as a long-running research and development program that has yielded invaluable design ideas. Long before human beings began tinkering in labs, organisms had developed carbon capture and sequestration systems, water harvesting techniques, water transport systems, adhesives, colorfast materials, electronic circuits, distributed energy conversion systems, color displays, light absorbers, insulation, thermal dissipators, and information storage, along with countless other designs. All of these are blueprints for technologies that are not only useful to society but are also integral to the global economy. Companies that learn from nature are increasing revenues, mitigating risk, reducing costs, and supporting the development of a sustainable society.

To understand how the biological world works—how it builds material, creates form, and constructs intricate systems—is to understand the inherent physical constraints of our planet. Organisms have operated within these rules for nearly 4 billion years, and human technology operates using the same rulebook.[3] Through bioinspired innovation, companies can not only discover design ideas in nature but also emulate nature by embedding sustainability into the development of new products and processes. By doing so, businesses can begin to see environmental challenges such as climate change as opportunities rather than economic risks.

The sequestration of carbon by corals inspired Blue Planet's cement additives made from waste CO_2 streams (see Carbon).

ACCELERATING INNOVATION

A flurry of innovation occurred in the twentieth century that had a positive, transformative effect on economies and societies.[4] Today, however, many companies and private investors develop and invest in "widgets [and] irrelevances" that neither produce healthy returns nor address pressing societal needs.[5] To develop the world-changing and profitable innovations of tomorrow, companies and investors need new sources of ideas.

Harvard Business School's Dr. Rosabeth Moss Kanter recently said that before innovation proves successful, it is merely "somebody's wild idea that competes with every other wild idea."[6] Indeed, technological innovation is an exercise in risk. Many businesses attempt to innovate by reformulating their existing products or emulating a competitor's product. However, these avenues often only provide incremental value to both businesses and society, not transformative breakthroughs.

Creating an entirely new product category that alters or creates markets (so-called "disruptive innovation") requires insightful strategy, serendipity, or both. Bioinspired innovation offers a real opportunity for companies to create products and processes inspired by proven designs: the attributes of organisms that perpetuate in nature because they solve particular challenges. Companies that leverage bioinspired innovation can increase revenues, reduce costs, and meet global needs. They can also increase their environmental, social, and corporate governance (ESG) rating, attracting investments from the $45 trillion managed by firms supporting this trend in financial markets.[7,8] By looking outside the bounds of their traditional disciplines, companies are able to transform markets and increase returns.

BIOINSPIRED INNOVATION

At Terrapin, we believe that natural systems offer solutions to industrial challenges. We believe that bioinspired innovation transforms businesses and industries, improves quality of life, and enhances the natural environment. This paper is a product of our experience developing bioinspired technologies and a testament to the potential we see in a bioinspired approach to research and development.

We work with companies, academic researchers, and governmental organizations to transition biologically-inspired technology into the market. Among our services, we:

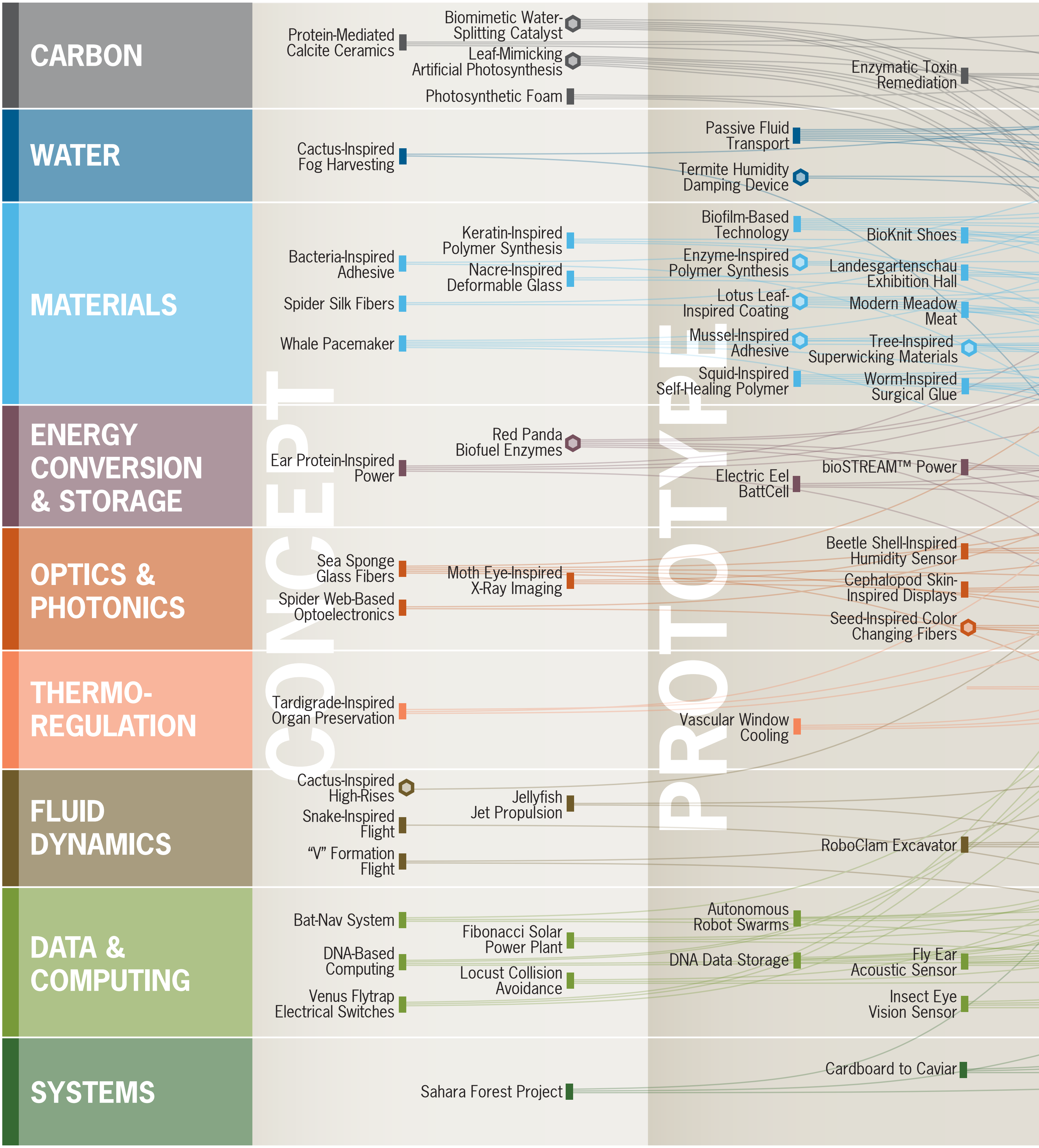
- introduce organizations to the biomimetic design process through presentations, case studies, and brainstorming workshops,
- provide biological research,
- evaluate technologies,
- partner with teams to co-develop technologies,
- advise on market needs and marketing language,
- connect research teams with strategic partners, and
- assist teams in securing funding for projects.

MARKET READINESS OF BIOINSPIRED INNOVATIONS

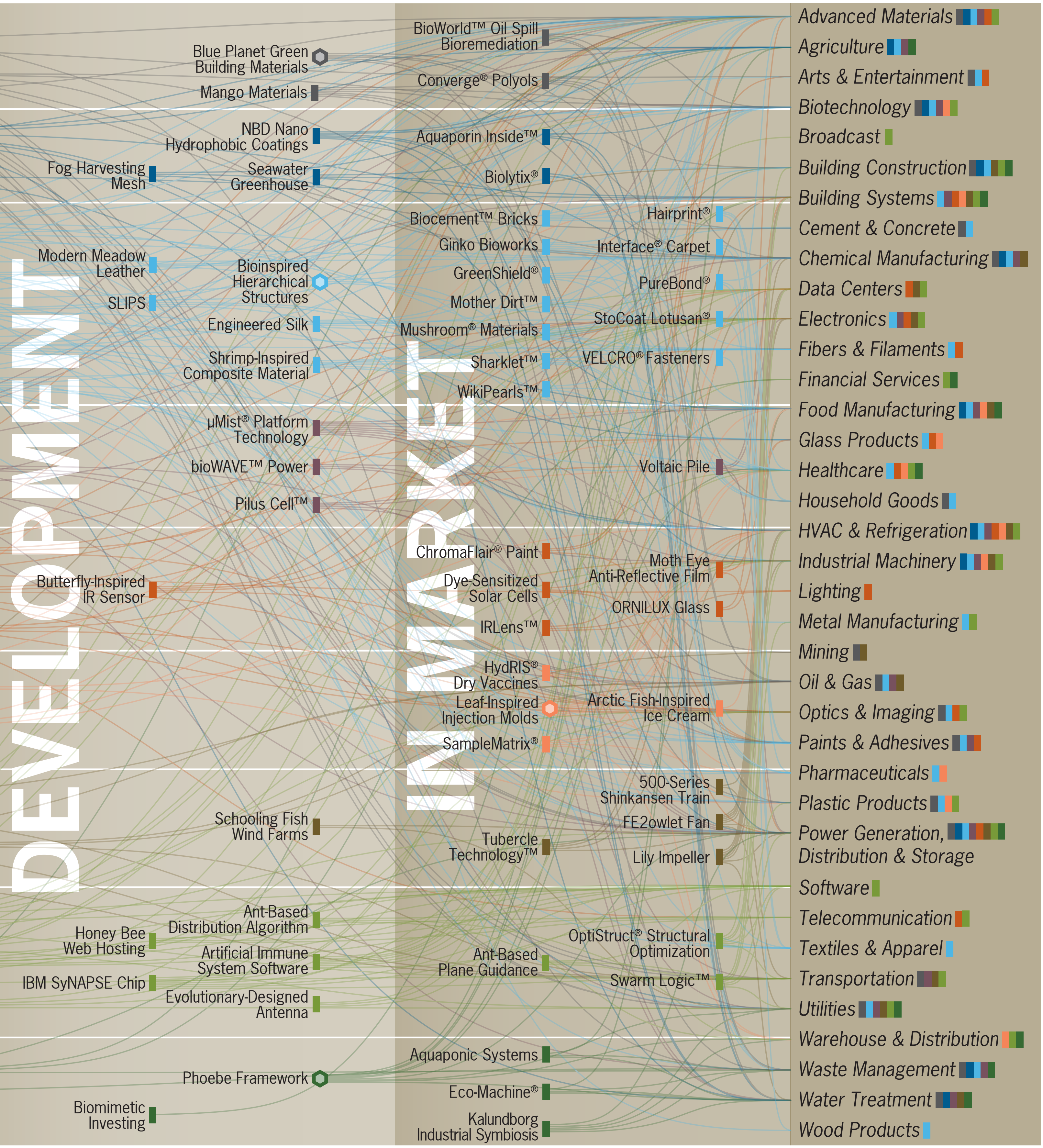
The infographic on the next page displays select bioinspired innovations, ranging from early concepts to fully commercialized products. These innovations are sorted according to the paper's cross-sector topics and connected to the various industries they influence. While many innovations are already commercially available, many more are in development and have the potential to create or disrupt markets.

Please visit the interactive web version of this infographic to explore the products and their industry connections in-depth available at: www.terrapinbrightgreen.com/report/tapping-nature.

MARKET READINESS OF BIOINSPIRED INNOVATIONS



This curated set of bioinspired innovations is sorted according to the topics on the left and connected to the industries they influence on the right. See Appendix for product descriptions. Several of Terrapin’s collaborations (⬢) are shown.



For product details, visit the interactive version at
www.terrapinbrightgreen.com/report/tapping-nature

BIOINSPIRED INNOVATION: AN ECONOMIC ENGINE

This section was prepared for Terrapin by the Fermanian Business & Economic Institute. It forecasts the economic impact that bioinspired innovation will have on gross domestic product and job growth by 2030 ($425 billion and 2 million jobs, respectively). Recent research and publications have established the Institute as a thought leader on the economic potential of bioinspired innovation. The Institute is a strategic unit of Point Loma Nazarene University in San Diego, California.

It is becoming increasingly clear that innovation and technological breakthroughs are not only keys to economic growth in the twenty-first century but also are necessary for human prosperity. The millions of materials and systems found in nature are a treasure trove of innovation, and companies can benefit by using these designs to reduce the time and costs associated with technology and product development. New channels of innovation, new products and markets, increased efficiency, and sustainability goals can all be realized through bioinspired innovation.

Many companies have profitably pursued the path of biologically-inspired innovation. Biomatrica, a rapidly growing biotechnology company, licenses a system for preserving and stabilizing biological samples based on processes observed in brine shrimp. Interface, the world's largest manufacturer of commercial carpet tiles, developed its best-selling product line by mimicking the random colors and patterns of the forest floor. PAX Scientific—founded on the insight that human hearts, birds in flight, and falling maple seeds use vortices to move fluid efficiently—has designed and sold their vortex water technologies to more than 1,000 customers, greatly reducing energy consumption at each installation.

While some concepts inspired by nature may disrupt existing markets, others may open up entirely new ones, as was the case with Qualcomm, which acquired the company Iridigm to form Qualcomm MEMS Technologies, or QMT. QMT developed low power, color display screens that can be viewed in full sunlight, a technology inspired by the way light interacts with the surface of butterfly wings. In recent years, the technology has been used in e-readers and smartwatches, allowing Qualcomm to enter into the electronic display market.

Sustainability initiatives are often driven by governmental regulations or the whims of individual managers. However, regulations can shift when economic growth or jobs appear to be in jeopardy, and a firm's management team may serve only a limited tenure. Shareholders will always look at underlying returns and profitability, but individuals and investment firms are increasingly considering environmental and social concerns. Bioinspiration offers a bridge between the seemingly incompatible interests of business and the environment. It is a compelling "win-win" approach: bioinspired innovation enables businesses to realize profit while also achieving sustainability goals.

TRANSFORMATIVE IMPACT

Bioinspired innovation has the potential to transform large segments of the U.S. economy by increasing both gross domestic product (GDP) and employment. The Fermanian Business & Economic Institute (Institute) estimates that bioinspired innovation could account for approximately $425 billion of U.S. GDP by 2030 (valued in 2013 dollars). Beyond 2030, the impact of bioinspired innovation is expected to grow as knowledge and awareness of the field expand.

The industries shown in Figure 1 represent the majority of the $425 billion that bioinspired innovation will contribute to 2030 GDP. The largest single-industry contributions are expected in building construction (including the cement and concrete sector), chemical manufacturing, and the power generation, distribution, and storage sectors. Some of the largest impacts of bioinspired innovation will occur in the manufacture of

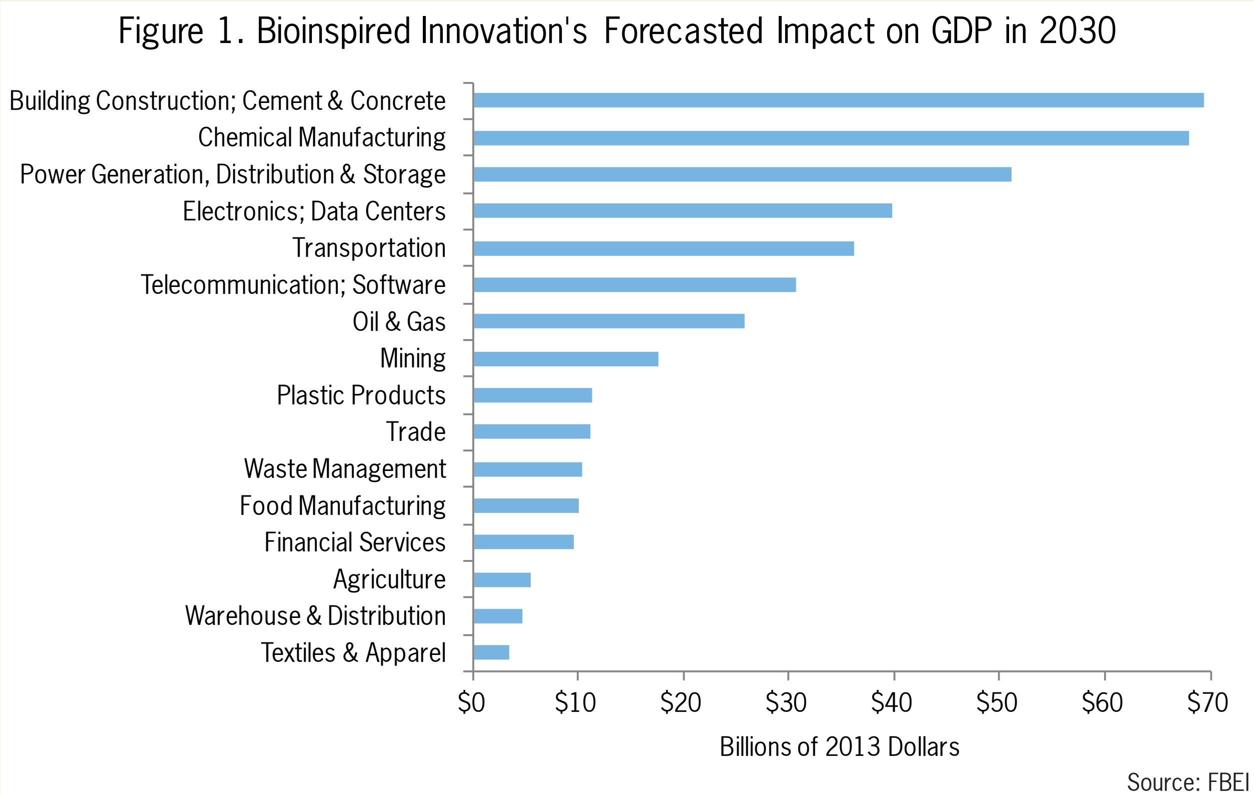


Figure 1. Bioinspired Innovation's Forecasted Impact on GDP in 2030
Building Construction; Cement & Concrete
Chemical Manufacturing
Power Generation, Distribution & Storage
Electronics; Data Centers
Transportation
Telecommunication; Software
Oil & Gas
Mining
Plastic Products
Trade
Waste Management
Food Manufacturing
Financial Services
Agriculture
Warehouse & Distribution
Textiles & Apparel
$0
$10
$20
$30
$40
$50
$60
$70
Billions of 2013 Dollars
Source: FBEI

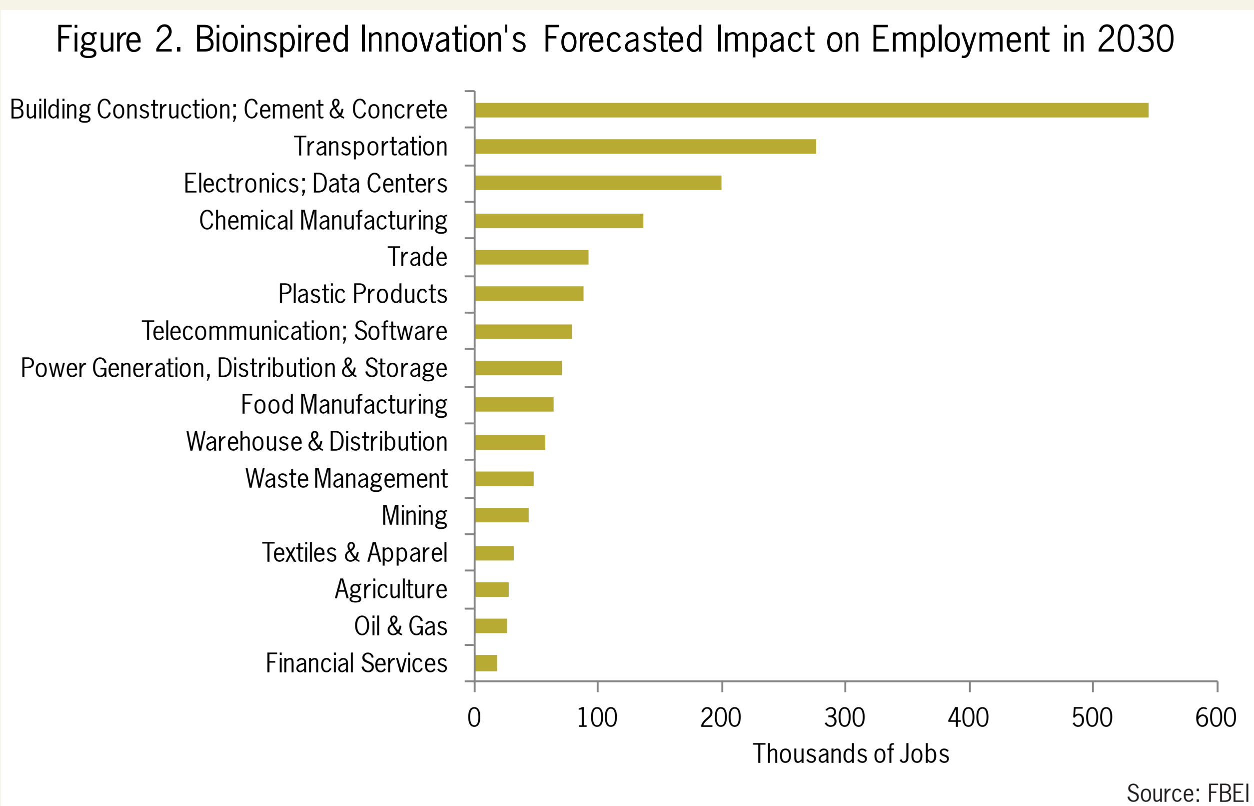


Figure 2. Bioinspired Innovation's Forecasted Impact on Employment in 2030
Building Construction; Cement & Concrete
Transportation
Electronics; Data Centers
Chemical Manufacturing
Trade
Plastic Products
Telecommunication; Software
Power Generation, Distribution & Storage
Food Manufacturing
Warehouse & Distribution
Waste Management
Mining
Textiles & Apparel
Agriculture
Oil & Gas
Financial Services
0
100
200
300
400
500
600
Thousands of Jobs
Source: FBEI

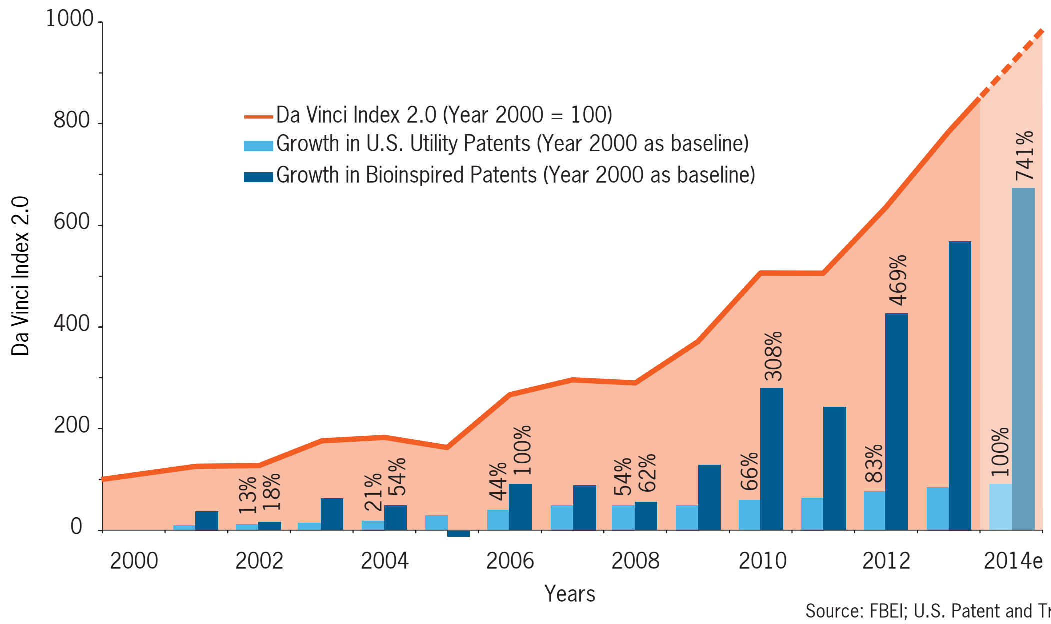
durable and nondurable goods due to the increased use of new bioinspired materials and processes. Also, there is a strong link between bioinspired innovation and energy; the transportation, oil and gas, and utility industries all stand to benefit from, or be transformed by, bioinspired innovation. In total, these sectors represent $113 billion—more than a quarter of the total forecasted GDP related to bioinspired innovation.

While bioinspired products will impact the economic performance of fields as diverse as transportation, electronics, and food manufacturing, they will also increase employment in these sectors. Reflecting the expected penetration in various industries, bioinspired innovation could generate approximately 2 million jobs by 2030 (see Figure 2).

TRACKING ACTIVITY IN BIOINSPIRED INNOVATION

The Da Vinci Index 2.0, which was created by the Institute, is derived from a comprehensive database that uses advanced methodology and information to measure activity in bioinspiration, biomimicry, and biomimetics. The Index monitors the number of U.S. patents issued, scholarly articles published, grants awarded by the National Science Foundation and National Institutes of Health, and the value of those grants for any given period. By extension, the Index offers insight into technologies in development at universities, research labs, and corporations. Granular data within the Index provides information on which fields of study are receiving the most attention and which regions of the world are most active in bioinspired innovation.

Figure 3. Da Vinci Index Growth Over Time



Source: FBEI; U.S. Patent and Trademark Office

The Da Vinci Index 2.0 (see Figure 3) is estimated to have reached a record high of just over 900 in 2014 (where the year 2000 equals 100), mainly due to a surge in published scholarly articles and steady growth of patents. The strong trend indicates the continued growth of bioinspired research and technology development. Compared to the keen interest recently expressed in “green tech,” bioinspired innovation offers less risk since it is less reliant on varying regulations (e.g., mandates for alternative energy sources or reduced pollution) and subsidies, which also fluctuate. As with any cutting-edge research, the challenge is to transition from compelling preliminary studies and ideas to tangible implementation and commercialization.

While total utility patent applications in the U.S. increased about 100% between 2000 and 2014, bioinspired patent activity has been much more active. Utility patents in the U.S. related to bioinspired innovation grew by nearly 750% relative to 2000 filings. Though investment returns for the bioinspired products developed from these applications will vary, investors looking for new ideas and investment opportunities will direct increasing amounts of capital to the field as it becomes better known through documented successes.

THE FUTURE OF BIOINSPIRED INNOVATION

Although bioinspired innovation holds enormous potential for the global economy, it still has far to go to fulfill its promise of transforming large portions of our economy. The vast majority of Americans, including company leaders and government policymakers, are not yet familiar with the idea of looking to nature to solve human challenges.

Bioinspired innovation clearly represents an appealing niche for financial and investment markets. It is an area that the Institute expects will provide sizable growth and profit opportunities to companies and financial service providers alike.

CARBON

Carbon is an integral part of life's "economy." Unlike the anthropogenic buildup of carbon in the atmosphere and ocean, carbon is used by organisms to accomplish functions, and it is exchanged in cyclic flows between organisms and regional ecosystems. The abundance of carbon dioxide (CO_2) and methane (CH_4) should be viewed as a ubiquitous resource and business opportunity.[9] Achieving goals like New York State's 80% reduction in greenhouse gas (GHG) emissions by 2050, relative to 2010 levels, will require not only easily achievable measures, such as retrofitting existing buildings to reduce energy use-related emissions, but also new strategies such as reusing carbon to ensure a prosperous low-carbon economy.[10] If properly funded, these additional reduction measures will come from bioinspired technology.

INDUSTRIES

Advanced Materials

Arts & Entertainment

Biotechnology

Building Construction

Cement & Concrete

Chemical Manufacturing

Household Goods

Mining

Oil & Gas

Optics & Imaging

Paints & Adhesives

Plastic Products

Power Generation, Distribution & Storage

Transportation

Utilities

Waste Management

Water Treatment

SELECTED STRATEGIES

CAPTURE

Carbon in the form of CO_2 is captured by a large subset of organisms in our ecosystems. Plants, algae, and cyanobacteria—all primary producers—supply the base layer of materials, or carbon feedstocks, to the ecosystem. Similarly, technologies currently in development will allow industry to capture carbon emissions directly from waste flue streams. GHG emissions produced by our economy can be captured and integrated into our existing material stream, moving us toward a cyclic carbon economy. Systems and materials that use waste carbon, such as Blue Planet's carbon-sequestering concrete, will create a much needed "sink" in the global carbon cycle and represent a huge economic opportunity for companies who accomplish this feat.[11]

STORAGE

The sequestration of carbon occurs in life's materials; all organisms are composed of carbon-based materials. The temporary storage of carbon in the ecosystem varies from days to eons, but carbon always moves through a cyclic process. In contrast, most of our synthetic materials and fuel move linearly from fossilized carbon to landfills, oceans, and the atmosphere. Companies and researchers are mimicking natural carbon storage by incorporating waste carbon into valuable fuels, polymers, and construction materials that comprise billion-dollar markets. Artificial photosynthesis is one such innovation that is beginning to tap and even expand these markets.

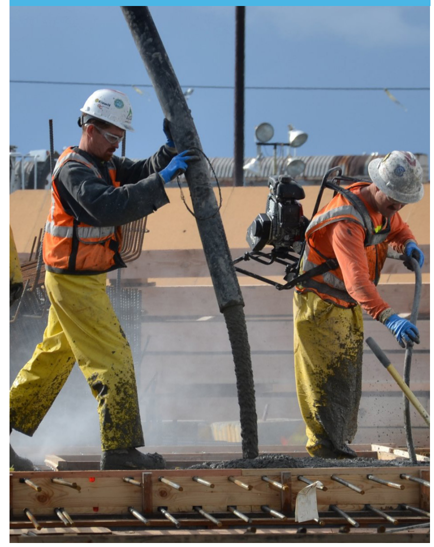
UTILIZATION

Carbon is cycled from molecule to molecule across organisms, incorporated into materials to meet various needs; the use of carbon is intimately connected to the storage of carbon. Often, stored carbon (whether from fossil or living sources) acts as a building block and as a temporary vessel for energy, allowing organisms to intake, store, and later use the carbon molecules as a material feedstock and chemical energy. Innovative companies, such as Novomer, are beginning to use waste CO_2-derived molecules when creating materials.[12]

EXISTING PRODUCTS

The production of one ton of cement typically results in the emission of approximately one ton of CO_2.[13] With the annual global production of cement at roughly 4 billion tons, the construction industry is a major carbon emitter.[14] California-based Blue Planet has developed a technology that captures CO_2 from flue gas and creates carbonate minerals to replace the Portland cement or aggregate components of concrete, or to be used in other green building materials. Their low temperature and low pressure process is inspired by the biomineralization of corals, which use dissolved CO_2 to grow solid reefs. The Blue Planet process has overcome the high capital and operating costs of similar technologies. When paired with a cement or coal plant's flue stream, the technology can produce concrete that is carbon negative. Scaled globally, Blue Planet could sequester more than ten billion tons of CO_2 over the next decade.[15] This type of technology is needed to reduce the 5-7% of global CO_2 emissions attributed to cement production and beyond.[16] Pilot scale operations are underway in the U.S.; Terrapin is working with Blue Planet to identify potential sites in New York State.

BLUE PLANET PRODUCTS



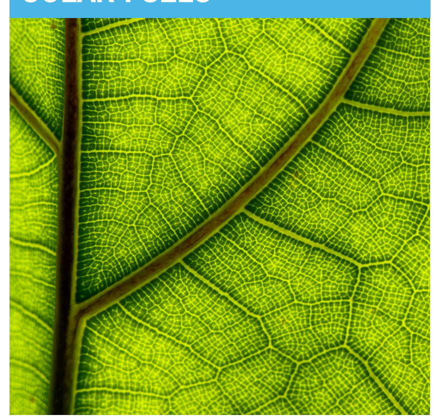
Conventional plastics, such as polyethylene and polypropylene, consist of chains of carbon atoms derived from petroleum. Novomer, a chemical company based in Massachusetts and New York, has taken inspiration from the carbon cycle in photosynthetic organisms and developed technologies that capture and utilize waste carbon monoxide (CO) and CO_2 in the creation of valuable polymers and chemical intermediates. Their proprietary catalyst enables the low temperature (~35°C/95°F) and low pressure incorporation of CO_2 into the molecular backbone of plastics, resulting in a CO_2/CO-derived carbon content of 50%.[17] Novomer's Converge® materials boast high performance metrics and cost competitiveness. After scaling to a production rate of thousands of tons per year, their products are currently being used in commercial applications by several adhesive and polyurethane manufacturers, including Germany-based Jowat AG.[18,19]

CONVERGE® POLYOLS

PRODUCTS IN DEVELOPMENT

The emerging technology artificial photosynthesis combines water, CO_2, and solar energy into liquid or gaseous fuel (solar fuels) in a process akin to photosynthesis. These high-energy molecules, such as methane and other hydrocarbons, hold the potential to seamlessly fit into our existing energy and transportation infrastructure. With assistance from Terrapin, Dr. Jiandi Wan of Rochester Institute of Technology is mimicking not only the system but the physiology of photosynthesizers by utilizing microfluidics and photochemistry to produce solar fuels. By emulating the small fluid channels seen in leaves, the device forces the reactants (CO_2 and water) into proximity, creating a more effective platform to chemically reduce them to solar fuels.[20] This elegant replication of photosynthesis takes advantage of readily available materials and sunlight.

SOLAR FUELS



WATER

Water, which is essential to life, is also essential to many industrial processes, systems, and energy technologies. Its presence or absence affects the energy demands of buildings, the growth and processing of agricultural products, the corrosion or fouling of materials, and the health of human populations. Increasingly, the use of water is threatened by limited access and availability of fresh water. Natural systems optimize the acquisition and use of water, gathering diffuse flows of water vapor and water from varied sources.

INDUSTRIES

Agriculture

Biotechnology

Building Systems

Chemical Manufacturing

Food Manufacturing

HVAC & Refrigeration

Power Generation, Distribution & Storage

Waste Management

Water Treatment

SELECTED STRATEGIES

FORWARD OSMOSIS

Almost 800 million people globally do not have access to potable water.[21] Providing drinking water in an energy-efficient manner is both a necessity and a business opportunity. All organisms leverage the natural phenomenon of osmosis—the movement of water across a membrane from one concentration to another—to their advantage. Plants and animals rely on this passive transfer to extract pure water from salt, brackish, and contaminated water sources. Mimicking osmosis may lead to scalable technologies for producing clean drinking water that can be deployed globally. Aquaporin A/S uses osmosis in its low-energy water filtration and desalination technology. The use of osmotic pressure to spin turbines—osmotic power—is also under development as a renewable energy source.

HUMIDITY CONTROL

Moisture—at high and low levels—poses a challenge to building environmental control systems and can degrade materials over time. Plants, however, maintain high humidity levels in the interior air spaces of their leaves through simple, responsive ventilation using openings on the bottom side of leaves. Also, termites impede humidity fluctuations by means of absorbent fungal structures.[22] A research team collaborating with Terrapin is investigating ways to mimic this and other strategies in a passive humidity damping device for application in buildings.

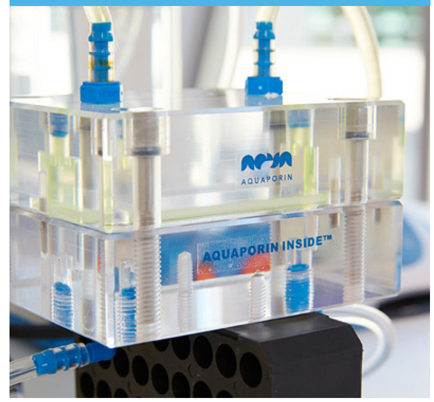
MOISTURE HARVESTING

Much of the water that humans use is in a liquid state, but several ingenious organisms harvest water vapor. A cactus native to Mexico uses its spines to collect water droplets from fog[23]; the Namib Desert beetle uses its black bumpy shell to condense water vapor[24]; and some bryophytes (mosses, liverworts, and hornworts) readily absorb moisture from the air.[25] Taking cues from nature, researchers at MIT and Pontifical Catholic University of Chile have tapped this resource. Their fog harvesting mesh technology can capture 10% of the water vapor contained in fog, offering a market-ready solution for semi-arid regions like Chile, where capturing only 4% of the water content in fog would meet the water needs of the nation's northern regions.[26]

EXISTING PRODUCTS

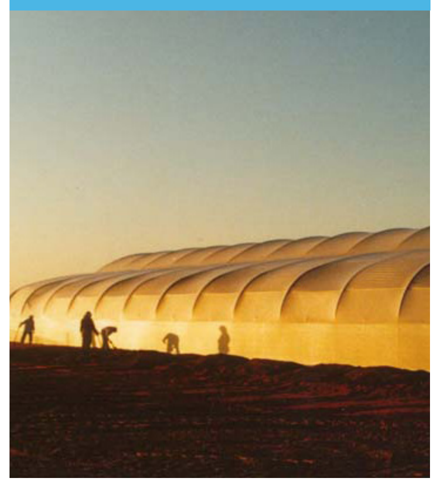
Aquaporin Inside™, commercialized by Aquaporin A/S, utilizes biological water transportation to filter wastewater, saltwater, and contaminated fresh water. All organisms have specialized water transport channels in their cells, called aquaporins, that selectively move water across membranes while preventing other molecules from passing through. Aquaporin A/S has embedded functioning aquaporins into water membrane technology to harness this water filtration capability.[27] The technique—a form of forward osmosis—reduces energy costs of water filtration by 80% compared to reverse osmosis filtration methods, which require high pressures.[28] In addition to manufacturing filters for current filtration equipment, the company has formed strategic partnerships to commercialize new applications in the Chinese and Singaporean markets.[29]

AQUAPORIN INSIDE™



Seawater greenhouse systems emulate the water harvesting strategy used by the Namib Desert beetle, which leverages the abundant solar resource, diurnal temperature differentials, and prevailing warm winds to condense humidity into fresh water. These systems distill seawater to grow crops year-round in arid climates where horticulture is otherwise cost prohibitive. The technology uses cool seawater, solar thermal systems, and warm, ambient air to evaporate and then condense water vapor into considerable volumes of fresh water. The Sahara Forest Project's Qatar pilot plant deployed this system to grow high-value food crops using 50% less water than comparable operations.[30] Seawater Greenhouse Ltd. and Australia-based Sundrop Farms have commercialized this technology and claim that reduced operating and fixed costs and the ability to use non-productive, inexpensive land results in up to 35% greater returns on invested capital than conventional modern greenhouses.[31]

SEAWATER GREENHOUSE



PRODUCTS IN DEVELOPMENT

In collaboration with Terrapin, researchers are currently developing a humidity damping device to passively dehumidify buildings in humid climates. The device is based on the fungal combs found in *Macrotermes* termite colonies, which help maintain the interior humidity level of the termite mound despite outside humidity fluctuations. These fungal combs—constructed by the termites as a food source—absorb water vapor from air in high relative humidity (RH) conditions and release it during times of low RH, passively regulating interior RH. To create this device, the team is experimenting with materials that mimic the absorption properties and the complex shape of the comb. Unlike current technologies such as enthalpy or desiccant wheels, the device would greatly reduce the amount of energy currently used in HVAC systems to maintain industry-standard RH levels and low RH levels in moisture-sensitive industrial processes.[32]

HUMIDITY DAMPING

MATERIALS

Materials—with their various strengths, finishes, and functions—underpin all industries, even those that involve intangible goods and services. Therefore, creating materials that provide superior performance at minimal cost is important to every business. Organisms, which "manufacture" their tissues at ambient conditions using locally available materials and energy, offer myriad examples of resource-efficient material manufacturing. Nature constructs these materials with a vast array of functions unsurpassed by many synthetic materials. It accomplishes this through nanoscale precision, using chemical elements in different proportions and atomic arrangements than synthetic materials.

INDUSTRIES

- *Advanced Materials*
- *Agriculture*
- *Biotechnology*
- *Building Construction*
- *Cement & Concrete*
- *Chemical Manufacturing*
- *Fibers & Filaments*
- *Food Manufacturing*
- *Glass Products*
- *Healthcare*
- *HVAC & Refrigeration*
- *Metal Manufacturing*
- *Oil & Gas*
- *Paints & Adhesives*
- *Plastic Products*
- *Textiles & Apparel*
- *Waste Management*
- *Wood Products*

SELECTED STRATEGIES

MULTISCALE STRUCTURES

Many biological materials have impressive levels of tensile strength, hardness, toughness, and other material properties unmatched by many of today's engineered materials. This is achieved in part through hierarchical ordering of material. At the nanoscale, seashell nacre is composed of calcium carbonate crystals deposited in a protein and carbohydrate matrix. These assemblies then form stacked tiles at the microscale. This multiscalar assembly, visible at the millimeter scale as 3mm thick layers, transforms brittle chalk into a tough ceramic. The structure of nacre has inspired tough, deformable glass.[2,33] Similarly, the waterproof adhesives produced by mussels owe their strength and stickiness to hierarchically crosslinked fibers. This attribute inspired the development of several biodegradable adhesives.

FUNCTIONAL SURFACES

Microscopic surface textures and chemical properties imbue biological materials with an astounding array of functions. Lotus leaves have waxy microscopic bumps that allow water to roll off and carry away dirt and particles. This "lotus effect" inspired the self-cleaning paint StoCoat Lotusan®.[34] Materials, such as the surface layer of the pitcher plant, wick water into microscopic ridges, creating super slick surfaces.[35,36] These concepts inspired anti-fouling surfaces such as SLIPS and superwicking surfaces for indirect evaporative cooling. Similarly, Sharklet™ mimics the scales of sharkskin to repel bacteria.[37,38]

"GROWN" MATERIALS

The ability to grow is an attribute of organisms that produces materials of remarkable complexity and functionality. When given the appropriate scaffolding and nutrients, cells replicate and self-assemble into mats, films, and various other forms. Using "biofabrication," or biology as a means of production, labs are able to generate valuable materials using relatively little energy. Materials like packaging foam, bricks, meat, and leather are "grown" using bacteria (bioMASON), fungi (Ecovative), and animal tissue cultures (Modern Meadow).

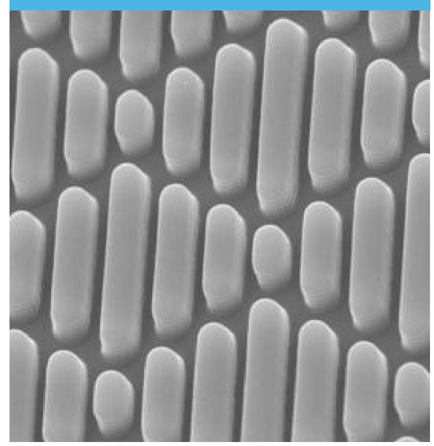
EXISTING PRODUCTS

When it rains, *Nelumbo* lotus leaves shed water droplets, dirt, and other particles with the help of micro- and nanoscale surface structures and gravity. This "lotus effect" is created by multiscaled, waxy bumps on the leaf surface that cause water to bead up and roll away.[39] Sto Corp., a Georgia-based manufacturer of building materials, duplicated this effect in the StoCoat Lotusan self-cleaning paint. The acrylic paint has a similar microtexture to the lotus leaf; it too sheds water and dirt, leaving a dry, clean surface on which algae and fungi have difficulty colonizing. Unlike exterior paints that become soiled over time, Lotusan's self-cleaning property makes it a low-maintenance, long-lasting coating for exterior applications.[40]

STOCOAT LOTUSAN®

Biofouling and antibiotic resistance are major concerns across many sectors, from maritime transportation to healthcare and food service. Sharklet Technologies, a Colorado-based biotechnology company, produces Sharklet™, an engineered microscopic topography inspired by sharkskin that reduces the growth of bacteria without the use of biocides. Like sharkskin, Sharklet surfaces feature a microscopic diamond pattern that prevents bacterial growth by up to 90% without contributing to antibiotic-resistant bacteria. Sharklet generated over $1 million in sales in 2012 and is co-developing furniture, medical devices, and consumer products with LG International, Cook Medical, Steelcase, and other companies. Sharklet is also developing urinary catheters that reduce the likelihood of catheter-related bacterial infections, which account for more than $565 million in healthcare costs in the U.S. annually.[38]

SHARKLET™



Ecovative, a New York-based materials science company, combines fungal mycelium—the vegetative portion of fungi—and agricultural byproducts to make environmentally-friendly Mushroom® Materials. These compostable materials are alternatives to plastic foam and other petroleum-derived synthetics. The manufacturing process begins by placing agricultural waste and a mycelium culture in a mold. As the mycelium grows, it binds the waste fibers into a solid mass that fills the mold. The mass is then heat-treated to stop the growing process, creating a material ready for use. Comparable in performance and cost to competing technology, Mushroom Materials are currently used as packaging and structural materials and as an environmentally-responsible replacement for engineered wood. Mushroom Materials are a Cradle to Cradle Certified[CM] Gold product.[41]

MUSHROOM® MATERIALS

EXISTING PRODUCTS (CONTINUED)

BIOCEMENT™ BRICKS

Due to the energy-intensive firing process, clay bricks account for an estimated 1.2% of the world's anthropogenic CO_2 emissions.[44] North Carolina-based biotech startup bioMASON has introduced Biocement™ bricks that are "grown" using bacteria. Combining sand, bacteria, water, nutrients, and nitrogen and calcium sources together in a mold, bioMASON creates bricks that are comparable in strength to traditional bricks. The bacteria cause calcium carbonate to precipitate between sediment grains, effectively cementing the mixture together into a hardened brick.[45] This process takes place at ambient temperature using locally-sourced materials and can occur on-site, drastically reducing the carbon emissions and embodied energy of the bricks.[46] bioMASON received an SBIR Phase I grant from the National Science Foundation and is currently scaling production capabilities from 1,500 bricks per week while also licensing the technology for use in on-demand manufacturing at construction sites.[47]

PRODUCTS IN DEVELOPMENT

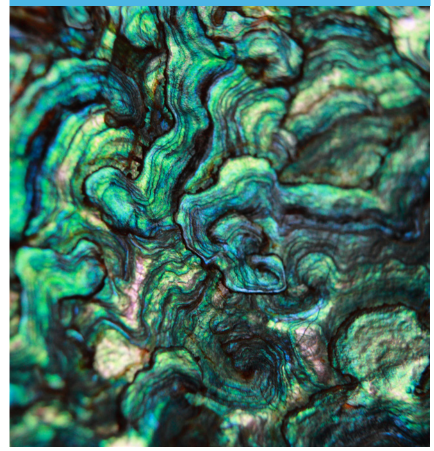
MUSSEL-INSPIRED ADHESIVE

Blue mussels (*Mytilus edulis*) produce a biodegradable, waterproof adhesive that attaches to almost any surface, even Teflon®. Most manufactured adhesives are not as versatile and contain toxic compounds like formaldehyde. Aided by Terrapin's competitive analysis services, researchers at the chemical company SyntheZyme are developing a water-resistant adhesive inspired by the mussel. The adhesive is made of proteins with chemically "sticky" ends that crosslink biopolymers into a strong matrix, chemically analogous to the mussel adhesive. It also uses a biological catalyst to achieve a low-energy synthesis. The polymers are renewable, nontoxic, and biodegradable. With the global adhesive and sealant market projected to reach $43 billion by 2020, and with demand increasing for nontoxic adhesives, this product could have a dramatic impact on the market.[42] Mussel adhesives have already inspired PureBond®, a commercially successful glue used in wood panel manufacturing.[43]

SUPERWICKING MATERIALS

Conventional vapor-compression air conditioners consume a great deal of energy and rely on refrigerants that are environmentally destructive when released. Terrapin advised Dr. Chunlei Guo's team at the University of Rochester on the market demand for their bioinspired superwicking material technology and assisted them in securing funds to develop energy-efficient indirect evaporative cooling. Leaves of the plants *Ruellia devosiana* and *Alocasia odora* have microscopic surface textures that trap water molecules, causing droplets to spread across the surface.[36] Mimicking this superwicking property, the research team fabricated materials with nano- and microscale features that wick large volumes of water, even up vertical surfaces. Such materials will increase the evaporation efficiency of cooling devices and, unlike the porous materials used in conventional evaporative coolers, they resist biofouling. The research team predicts a five-fold decrease in the energy consumed to cool buildings with this novel air conditioner.

DEFORMABLE GLASS

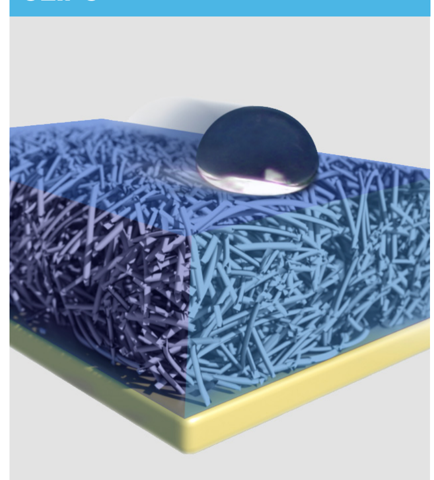


Although mainly composed of chalk, nacre found in seashells has astounding fracture resistance. Researchers at McGill University believe nacre owes its unique properties to a network of microcracks between brittle calcite plates that are filled with sticky polymer. Translating this idea, the team laser-engraved a 3D array of microscopic cracks in glass and filled them with polyurethane. The microcracks inhibit larger cracks from forming by deflecting and dissipating stresses, making this modified glass 200 times tougher than standard glass.[48] The researchers believe the polyurethane fill makes little difference; simply engraving microcracks may be enough to toughen brittle materials, which could mean that the carcinogenic polyurethane can be avoided in the future.[49] The engraved glass deforms without shattering, making it ideal for windows, electronics, and glassware. The team also believes the same strategy can be applied to other materials that suffer from brittleness, like ceramics.[50]

MODERN MEADOW

Livestock production accounted for at least 18% of the world's GHG emissions in 2006.[51] It also requires 33% of the world's arable land and 8% of the world's water. Using novel tissue engineering techniques, Modern Meadow is producing lab-grown food and materials to make products analogous to—and better than—those produced from animals. Instead of using resources to raise and slaughter, the process takes a culture of cells from an animal and prompts the cells to grow into tissues similar to skin and muscle. Compared to current livestock production, this process could reduce the use of arable land by 99%, water by 96%, and energy by 45%, while emitting 96% less GHG emissions. The production process also avoids the heavy use of antibiotics and the ethical dilemmas associated with current livestock operations. Modern Meadow has successfully produced samples of leather in a variety of colors and thicknesses. The company, currently focused on leather production, envisions leather that is customizable by shape, texture, and breathability.[52,53]

SLIPS



Inspired by the *Nepenthes* pitcher plant, researchers at Harvard University's Wyss Institute of Biologically Inspired Engineering developed an extremely slippery surface that repels most liquids and biofilms. The slipperiness of the pitcher-shaped leaf is caused by microscopic surface corrugations that hold water, forming a thin film.[35] The researchers adapted this idea, creating a microstructured porous material which holds a specially formulated liquid lubricant. The surface is so slippery that even crude oil and liquid asphalt roll off it. Unlike engineered hydrophobic surfaces, this surface "self-heals" since the lubricant fills scratches as they occur. The porous medium can be applied onto many surfaces. Slippery Liquid-Infused Porous Surfaces (SLIPS) has many potential applications such as anti-fouling, anti-icing, chemical and fluid handling, corrosion prevention, and pest control.[54,55] SLIPS Technologies, Inc. was founded in 2014 to further develop the many commercial applications explored by the researchers while at the Wyss Institute.[37]

ENERGY CONVERSION & STORAGE

Energy conversion allows us to leverage energy sources for useful work. Whether it is converting stored chemical energy (fossil fuels) to thermal energy or transforming photons (sunlight) to electrical energy, the energy industry hinges on the efficient storage and conversion of energy. In nature, entire ecosystems are structured around variable and limited energy sources, forcing organisms to optimize energy conversion and storage to ensure their survival. Consequently, nature has evolved many energy strategies barely explored by today's businesses.

INDUSTRIES

Advanced Materials

Agriculture

Biotechnology

Building Systems

Chemical Manufacturing

Electronics

Food Manufacturing

HVAC & Refrigeration

Industrial Machinery

Oil & Gas

Paints & Adhesives

Power Generation, Distribution & Storage

Transportation

Utilities

Waste Management

Water Treatment

SELECTED STRATEGIES

DISTRIBUTED CONVERSION

Ecosystems are driven by readily available, distributed, and renewable energy sources. Individual organisms make use of solar, chemical, wind, and gravitational potential energy—all uncentralized sources—to move, sense, migrate, and otherwise accomplish tasks. Maple tree seeds disperse using the wind; plant roots orient using gravity, which guides root tips downward[56]; living things use the energy flows that surround them. Many businesses have adopted similar strategies, relying on distributed renewable energy sources to power their operations, thus reducing long-term costs. Products inspired by the use of readily-available energy flows include BioPower Systems' wave- and tide-powered electric generators.

CHEMICAL STORAGE

Organisms rely on transient, distributed energy sources, which force them to store captured energy in the form of long-lasting chemical fuel. Unlike our current electrical grid that produces energy for immediate consumption, organisms capture energy, store it in chemical bonds, and expend these fuels as needed. As we transition to using transient, renewable energy sources, our energy infrastructure will require a similar storage strategy. In development today, solar fuels produced from artificial photosynthesis could be integrated into our current infrastructure and boast the same beneficial properties of biological fuels.

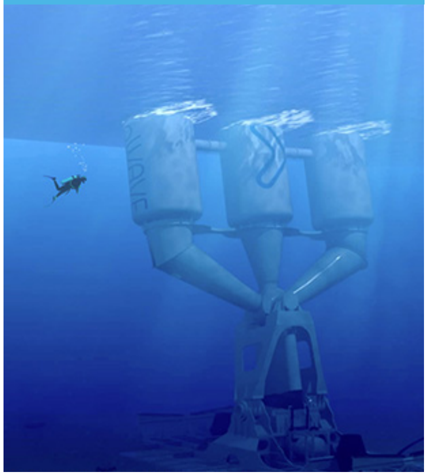
FUEL DIVERSITY

Most of our cars, engines, and power plants run on a narrow range of fossil fuels. In contrast, animals metabolize a variety of fuel sources such as fats, proteins, and carbohydrates. Some microbes consume an even greater range of "fuels," metabolizing cellulose, iron, sulfur compounds, and ammonia.[57,58] Utilizing the mechanisms of microbes, researchers are attempting to modify engines and other power generation devices to consume a greater variety of readily-available, renewable fuels. One example is the Pilus Cell™, which harnesses the metabolic activities of specialized bacteria to break down organic compounds in wastewater, producing electricity, valuable chemicals, and clean water.

EXISTING PRODUCTS

Ocean waves carry a large amount of energy, but this resource remains largely untapped due to the power delivery and lifespan challenges facing the current generation of wave energy capture devices.[59,60] BioPower Systems, an Australia-based renewable energy technology company, addressed these issues by observing how aquatic plants and algae sway in ocean swells without suffering much damage.[61] They developed the bioWAVE™ system, which features a unique "frond" structure consisting of three air-filled paddles fixed to a submerged lever that pivots back and forth with the waves, generating electrical power. The self-regulated O-Drive™, a hydraulic power converter in the base, delivers consistent power despite fluctuations in wave intensity. When wave intensity is too high, the paddles automatically fill with fluid, sinking the structure into its "safe" position on the seafloor. A $15 million demonstration project is underway in Port Fairy, Australia to test the 250kW bioWAVE, paving the way for future 1MW commercial installations and wave energy farms.[62]

BIOWAVE™ POWER



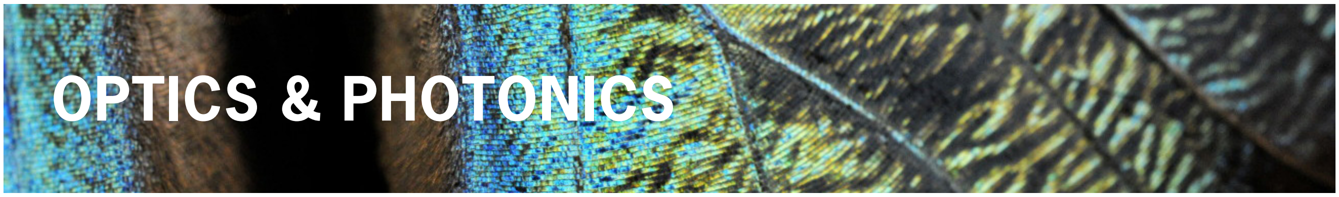
Researchers at University of Leeds and Cornell University have developed the µMist® Platform Technology, a spray system inspired by the defense mechanism of bombardier beetles. Using a unique valve system, the 2 cm/0.78 inch-long beetles are capable of spraying pulses of boiling liquid distances of up to ten times the length of their bodies. The team studied the valve to develop µMist, which can spray small vapor droplets using lower injection pressures than other systems.[63,64] The ability to reliably deliver uniformly small droplets of fuel allows internal combustion engines to convert chemical energy to thermal energy more efficiently, resulting in a more efficient combustion cycle and decreased GHG emissions. Swedish Biomimetics 3000, the sole licensee of µMist, has collaborated with Lotus and Cosworth, both U.K.-based automobile companies, to develop new fuel injection systems.[65,66] The technology also has applications in personal care, drug delivery, and fire protection.[67]

µMIST® TECHNOLOGY

PRODUCTS IN DEVELOPMENT

The "waste" in wastewater from manufacturing, food processing, and sanitation contains approximately ten times more energy than the amount used to treat it, and wastewater treatment is an energy-intensive process.[68] The Pilus Cell™, a microbial fuel cell in development by the Ohio-based synthetic biology company Pilus Energy, generates electricity, clean water, and valuable chemical products from wastewater. Pilus Energy's technology uses genetically modified bacteria to break down the organic molecules in wastewater, generating molecules such as methane and isoprene. The Pilus Cell has been approved for pilot testing at the EPA Test & Evaluation Facility to demonstrate its potential use in industrial sewage treatment plants.[69] Pilus Energy was recently acquired by Tauriga Sciences, a diversified life sciences company.[70]

PILUS CELL™



OPTICS & PHOTONICS

Controlling the capture and emission of light is an important function in both organisms and industry. The manipulation of light—known as photonics—includes the generation, detection, absorption, scattering, and processing of light. Illuminating spaces, absorbing sunlight, and transmitting data optically are vital to today's economy. Innovations in photonics, including those inspired by nature, have allowed companies to create and power many of today's products. Due to increasing energy costs, the efficiency of these products is critical to their success in the marketplace, to operational costs for consumers, and to the competitiveness of their manufacturers.

INDUSTRIES

- *Advanced Materials*
- *Arts & Entertainment*
- *Building Systems*
- *Data Centers*
- *Electronics*
- *Fibers & Filaments*
- *Glass Products*
- *Healthcare*
- *Lighting*
- *Optics & Imaging*
- *Paints & Adhesives*
- *Power Generation, Distribution & Storage*
- *Telecommunication*

SELECTED STRATEGIES

LIGHT ABSORPTION

Numerous animals and plants employ materials and nanoscale architectures to ensure that light is absorbed.[71,72] They offer blueprints for nanoscale designs to absorb broad or narrow ranges of the light spectrum, important when creating anti-reflective surfaces to increase solar cell efficiencies. Bioinspired nanoscale geometries create anti-reflective surfaces, allowing more light to transition between materials compared to unstructured surfaces.[73] A notable application of this strategy is the anti-reflection films that improve light absorption in commercial solar cells. These films mimic the low reflection of moth eyes.

LIGHT REFLECTION

The reflection of light is important to many technologies aimed at visual signaling and data communication, including traffic signs and road markers, reflective surfaces in spectroscopy equipment, back reflectors on flat screen displays and LEDs, and many important industrial processes. Stacking or concentric layering of materials in organisms often creates reflective surfaces. The iridescent, layered cell architecture of the seeds of the tropical fruit *Margaritaria nobilis* has inspired a photonic fiber that reflects varying colors when stretched.[74] The fiber could be used in a wide range of applications including visual detection of mechanical failure. Additional technologies are being developed using this strategy to create structural color—coloration independent of chemical pigments.

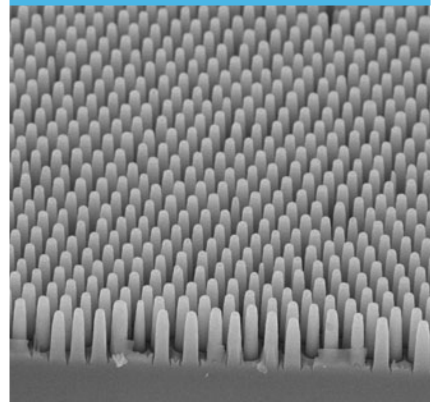
LIGHT GUIDING

Light can be guided by a material rather than simply absorbed and reflected. Many commercially available optical devices, such as the IRLens™, are based on how eye structures guide light.[75,76] Guiding visible light accurately is particularly crucial to optical chip technologies, which could replace conventional electronic chips for faster data transmission. Certain biomaterials, such as iridescent beetle shells and sea sponges, provide inspiration for novel manufacturing techniques for light guiding devices.[77] Although no commercially available photonic products have been realized to date, bioinspired photonic structures will allow light to be manipulated and guided in future optoelectronic devices.

EXISTING PRODUCTS

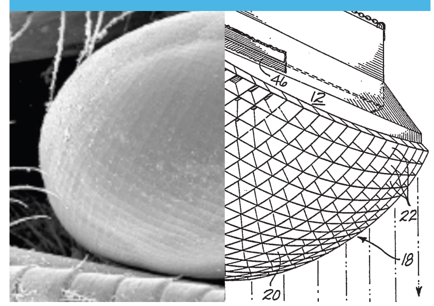
Nocturnal moths have eyes that absorb a high proportion of light, allowing them to see in very low light conditions. Nanoscale structures in their eyes advantageously direct incident light to increase the insect's light sensitivity and decrease external reflection visible to predators. One of the specific components responsible for this sensitivity, the "moth-eye" structure, covers the micron-sized facets of the eye and acts as an anti-reflective coating. Nagaoka University researchers emulated this structure to develop moth-eye films for existing solar arrays, and researchers in the U.S. have developed manufacturing techniques to incorporate moth-eye nanostructures during solar cell production.[78,79] Researchers have shown that anti-reflective moth-eye films increase the conversion of incident photons to usable electricity by 5-10%, a welcome improvement for any solar cell technology.[80,81]

ANTI-REFLECTIVE FILMS



Heating only essential spaces, rather than an entire room, enables facilities to reduce their energy demand. The IRLens in HotZone® radiant heaters uses the same principle seen in the eyes of lobsters, crayfish, and shrimp—focusing light on specific areas—to direct infrared light. After being commercialized into a $1 million business, the technology was licensed to Schaefer Ventilation. Energy costs can be reduced by 50% or more thanks to the device's bioinspired lens. The HotZone heater is able to double the efficiency of conventional spot heating technology, delivering 85% of the source energy to the area requiring heating.[75,82,83]

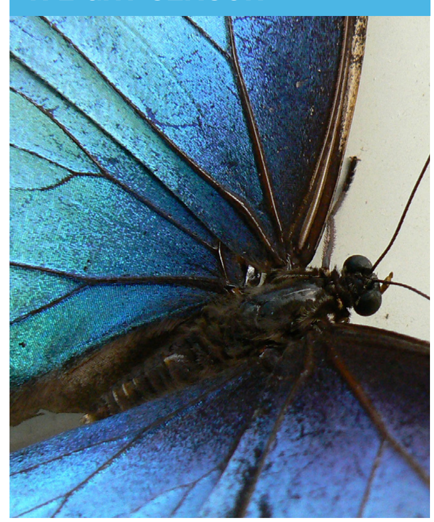
IRLENS™



PRODUCTS IN DEVELOPMENT

The wings of *Morpho* butterflies produce vibrant, iridescent colors when light interacts with the nano- and microscale architecture of their wings. The wings are comprised of scales made of chitin—an abundant biopolymer—and each scale supports an array of minute parallel ridges. A cross-section of each individual ridge shows a branched, periodic nanoscale structure. GE Global Research has determined that the scales have an optical response to changes in thermal energy. Absorption of IR photons and a subsequent conversion to thermal energy by the chitin results in an expansion of the nanostructure; this physical change results in an observable change in the wing's iridescence. The speed and sensitivity with which the wing scales react to IR photons were previously unattainable in manufactured thermal sensors. New thermal sensors based on the nanostructure of *Morpho* wings are being developed to improve not only response speed and thermal sensitivity but also to reduce their pixel size.[84] Continued research of photonic structures in nature may spur a new generation of sensor technologies.

IR LIGHT SENSOR



THERMOREGULATION

Introducing, removing, or excluding thermal energy is required for many products and systems such as adding or ventilating heat from buildings, manufacturing consumer products, and operating industrial machinery. How these flows and fluctuations of heat are managed often determines the efficiency of a design, and thermoregulation can be costly to manufacturers and consumers. Many organisms have developed replicable, low-energy strategies to maintain constant body temperatures despite temperature fluctuations in their environment, while others have developed methods to function despite extreme temperatures.

INDUSTRIES

Advanced Materials
Biotechnology
Building Systems
Fibers & Filaments
Food Manufacturing
Glass Products
Healthcare
HVAC & Refrigeration
Industrial Machinery
Lighting
Pharmaceuticals
Plastic Products
Textiles & Apparel
Warehouse & Distribution

SELECTED STRATEGIES

HEAT EXCHANGERS

The surface area to volume ratio of an organism is calibrated to its habitat. Plants and animals in hot climates typically have large surface areas relative to their volume, while cold climates feature organisms with relatively small surface areas. In addition, organisms contain branching webs of veins and other fluid-containing channels to exchange heat with their surroundings.[85] These two strategies suggest ways of tailoring convective heat transfer in buildings, manufacturing processes, and advanced machinery. Harbec is incorporating internal cooling channels in their injection molds, mimicking vascular systems to remove thermal energy more effectively.

ANTIFREEZE MECHANISMS

Plants, animals, and microorganisms survive freezing temperatures using a range of remarkable strategies.[86] Antifreeze molecules found in organisms like arctic fish, beetles, yeast, and bacteria inhibit ice crystal growth by binding to ice crystals before they expand and aggregate.[86-88] These molecules are of great interest to companies such as fuel cell manufacturers that want to prevent liquid fuel from freezing and food manufactures like Unilever, which uses an antifreeze protein to create creamier ice cream.[89]

THERMAL STABILITY

To survive elevated temperatures and extreme dryness, certain organisms chemically stabilize their proteins and tissues. Microorganisms that thrive at high temperatures feature enzymes that function up to 110°C/230°F. These enzymes were instrumental in the development of the revolutionary genetic analysis technique known as PCR.[90,91] Organisms, such as the tardigrade, are capable of withstanding not only high temperatures but also desiccation. This inspired the development of dry vaccines and biological preservation technologies commercialized by Nova Laboratories and Biomatrica.[92,93] Cold storage is unnecessary due to the products' ability to maintain the integrity of thermally-sensitive chemical compounds, reducing shipping and storage costs.

EXISTING PRODUCTS

Nova Laboratories mimicked the extreme desiccation abilities of certain organisms to develop “dry” vaccines. Standard vaccines contain biological material that must be refrigerated, requiring energy intensive supply chains (known as “cold chains”) that keep the vaccines at low temperatures from manufacture to administration.[94] Nova’s dry vaccine platform technology (known as HydRIS®) preserves the vaccine material in a dry, sugar glass matrix for transport. The vaccines are rehydrated just before administration to the patient. This platform technology creates chemically and physically stable vaccines while withstanding temperatures of 0-50°C/32-122°F without compromising potency, saving on energy and transportation costs and allowing vaccines to be transported to remote areas.[95]

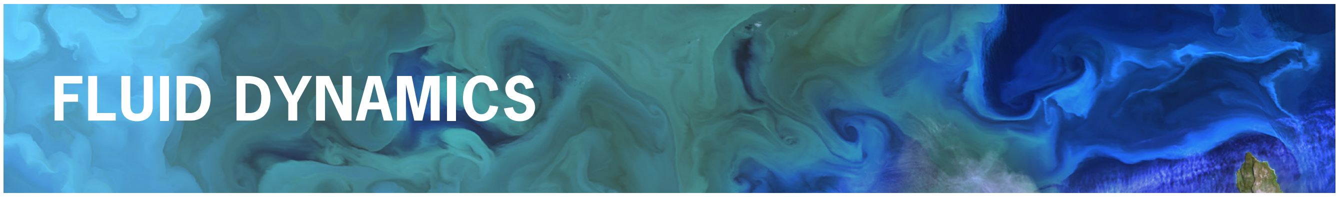
HYDRIS® DRY VACCINES

Ice cream—a $60 billion market in 2013—requires considerable energy throughout its refrigerated supply chain.[96] The texture of ice cream is dictated by the small size and regularity of its ice crystals. If ice cream thaws and refreezes, ice crystals grow and accumulate, decreasing the quality of the product. In developing economies, however, refrigeration is not always available. Recently, product manufacturer Unilever introduced an ice structuring protein first identified in arctic fish to prevent the growth of ice crystals.[97] Approved by the U.S. FDA and its counterparts in the European Union and Australia, this ingredient allows ice cream products to undergo freeze-thaw cycles with minimal crystal growth, ensuring a high quality product reaches consumers even over imperfect supply chains in warm climates.[98]

UNILEVER ICE CREAM

The manufacture of injection molded plastic parts involves both the introduction of high thermal energy and its removal. Cooling fluids are used to extract the supplied heat from each part, creating an energy-intensive process. New York-based plastics manufacturer HARBEC tapped Terrapin’s network of biomimicry experts and built a multidisciplinary design and engineering team with Dr. Jiandi Wan of RIT and Dr. Abraham Stroock of Cornell University. Applying a biomimetic approach to the redesign of the metal molds, the team looked at natural systems that are effective at dissipating heat, such as arteries in the depths of mammalian brains, webs of vessels embedded in large ears and leaves, and channels in termite mounds and the human lung. The new molds mimic dicot leaves and feature webs of cooling passages rather than the simple, straight cooling channels found in conventional molds. The bioinspired molds allowed HARBEC to reduce cooling times and energy consumption by more than 20% compared to conventional molds. Read more about this project in Terrapin’s case study.

INJECTION MOLDING



FLUID DYNAMICS

Fluid dynamics describes how liquids and gases move and aims to limit the effects of drag. Every object in motion encounters the momentum-sapping effects of friction and drag from surrounding fluids. Modern society uses excessive amounts of energy to overcome these effects in many industries. From single cells to humpback whales, organisms move fluids—and move through them—using minimal energy. Studying their movements helps improve the energy profile of companies in industries such as utilities, warehouse and distribution, manufacturing, and transportation.

INDUSTRIES

Building Construction

Building Systems

Cement & Concrete

Chemical Manufacturing

Data Centers

Electronics

Food Manufacturing

HVAC & Refrigeration

Industrial Machinery

Mining

Oil & Gas

Power Generation, Distribution & Storage

Textiles & Apparel

Transportation

Utilities

Water Treatment

SELECTED STRATEGIES

VORTICAL FLOWS

Vehicles, structures, and industrial equipment such as pipes, ducts, engines, and turbines are often streamlined to create idealized laminar flow but suffer energetic losses or mechanical failure when these flow patterns break down. Animals and other organisms leverage idealized vortical flows such as spiraling eddies. By exploiting or even creating vortices instead of trying to avoid them, flocking birds, swarming insects, schooling fish, and the human heart are able to move through fluid and move fluid with minimal energy expenditure.[99] Companies, such as PAX Scientific, are using these insights to provide new, low-energy processes and increased power production.

CONSTRUCTAL THEORY

Fluid flow in nature always follows the most efficient path. This phenomenon can be described by constructal theory—the study of how living and nonliving systems in nature optimize flow systems.[100] The flow of air in human lungs, nutrients in leaves, and water in river deltas follows this principle, balancing various “flow resistances” to create systems that minimize expended energy. Flow resistances are any aspect of the system that interact with the fluid’s movement; optimizing these simultaneously will result in designs with superior performance. Harbec is using constructal theory in the design of their injection molds, mimicking vascular systems to move coolant, and thus thermal energy, more effectively.

EXISTING PRODUCTS

Fans, mixers, pumps, and propellers all aim to move fluid—air, water, and the like—using as little energy as possible. The Lily Impeller designed by PAX Scientific, a California-based technology firm, creates spiraling flows to move fluid. The same strategy—using vortices—is employed by birds in flight and schools of fish.[99] The importance of this spiraling design is that it allows fluid to flow with reduced friction, minimizing the energy needed to move material from one point to another. PAX's technologies are tailored for specific industries, offering reduced energy inputs, reduced operating noise, and efficient mixing over conventional technology. PAX Water—aimed at water and wastewater treatment—can effectively circulate 10 million gallons of water using the same power as three 100 watt light bulbs. This is much less power than conventional technology requires and has been installed at 1,000 sites.[101] PAX Mixer technologies—focused on industries where fluid mixing is critical—are able to reduce required energy inputs, capital costs, and mixing time, while increasing product yields.[102]

LILY IMPELLER

Commercialized by Toronto-based WhalePower, Tubercle Technology™ emulates the vortex-forming bumps on humpback whale fins. The small vortices created by whales' tubercles delay stalling effects, permitting a 40% increase in the angle of attack before flow separation occurs and reducing drag by 30%.[99,103] Envira-North Systems has partnered with WhalePower to use this technology in high-volume, low-speed ceiling fans. Compared to conventional fans, these tubercle-enabled fans reduce power consumption by 20% and reduce operating noise.[104] WhalePower is also commercializing their technology for the wind energy industry, providing reductions in both turbine noise and mechanical fatigue.

TUBERCLE TECHNOLOGY™

PRODUCTS IN DEVELOPMENT

Unlike horizontal-axis wind turbines (HAWTs), which are costly to purchase, install, and maintain, and require large expanses of land, vertical-axis wind turbines (VAWTs) offer closer spacing, omnidirectional operation, and lower capital and maintenance costs. Dr. John Dabiri at CalTech has patented a bioinspired design for VAWT farms. Informed by the vortices of schooling fish, Dr. Dabiri has shown that counter-rotating, closely-spaced turbines minimize the negative effects of turbulence in VAWT farms. Though VAWT farms produce less power output overall, the spatial arrangements recommended by Dabiri result in wind farm power densities that are ten times higher than HAWT farms (30 W/m^2 compared to 3 W/m^2), decreasing a system's footprint and enabling medium and large sized VAWT installations to be more readily adopted.[105] Dabiri's designs have been implemented at an existing wind farm to improve power density and in Igiugig, Alaska, to provide high power output in this remote village.[106] This innovative approach yields reductions in cost, wind farm size, and environmental impacts.

WIND FARMS

DATA & COMPUTING

Data is a signal. Information is the meaning of the signal, and knowledge is the recognition of patterns in that meaning. Intelligence—the ability to turn data into knowledge—has not been achieved in conventional computing. Computers can calculate numerically but cannot learn or handle complex situations like living organisms do. Even human intelligence cannot match the continual design optimization of biological evolution. Many developers recognize the limits of conventional data handling and have mimicked nature to create novel sensors, computing architectures, software, autonomous robots, and other intelligent designs.

INDUSTRIES

Biotechnology

Building Construction

Building Systems

Data Centers

Electronics

Financial Services

Healthcare

HVAC & Refrigeration

Industrial Machinery

Optics & Imaging

Power Generation, Distribution & Storage

Software

Telecommunication

Transportation

Utilities

Warehouse & Distribution

SELECTED STRATEGIES

SENSING & SIGNALING

Many species rapidly assess environments with remarkable sensing and signaling mechanisms. Compound insect eyes, which perceive movement faster than traditional cameras, have inspired vision sensors for aerial systems and robotics.[76] Swarming bees, birds, ants, and bacteria signal to one another to coordinate movement, food gathering, and danger avoidance, forming a collective intelligence. Swarm intelligence, inspired by this signaling, has enabled companies like Encycle, Southwest Airlines, and Air Liquide to efficiently resolve complex problems.[107,108]

DATA STORAGE

Just as computers and server farms store data, organisms store and retrieve (i.e. remember) data relating to food, predators, and habitats. Accordingly, biological brains have very dense storage capabilities. Though brains and computers store data very differently, the human brain can store approximately 3.5 million gigabytes, roughly 55,000 times more than a 64 gigabyte iPad.[109] Additionally, all life requires heritable instructions (data-dense DNA) to direct growth and development. Researchers at Harvard's Wyss Institute coded 700 terabytes of data into 1 gram of DNA, prompting interest in DNA as a storage medium. The team believes that with improvements, all the data in the world (nearly 1.8 billion terabytes) could theoretically be stored in about 4 grams of DNA.[110]

INTELLIGENCE

Nature achieves intelligence in ways unrealized by today's computing, such as the brain's ability to learn and respond, the collective task coordination of cells and immune systems, and the optimization of evolution.[111] Bioinspired computing is becoming essential to modern computing; artificial neural nets, such as IBM's SyNAPSE chip—based on neuron organization in brains—can process in parallel and learn. Artificial immune systems mimic the dynamics of immune systems, improving computer security, fault detection, and machine learning. Evolutionary algorithms used in software, such as Optistruct®, are based on the principles of evolution: they generate optimal solutions from a field of iterations, saving design time, and improving functionality.[107]

EXISTING PRODUCTS

Electricity used during peak periods of demand can account for 20-50% of a facility's electric bill due to the use of "peaker" power plants by utilities to meet demand. Technology developer Encycle created a building management system that mimics the communication system of bee colonies; each piece of equipment simultaneously senses and communicates with one another without using top-down management to minimize power consumption. Their Swarm Logic™ controllers reduce peak demand by roughly 25% and the overall energy consumption of buildings by 15-30%.[112] Installed on each HVAC unit or other discretionary electrical load, the devices communicate with each other wirelessly, each deciding whether to switch its unit on or off depending on the cycles of other units. This coordination ensures that the fewest possible units are running at any given time without compromising occupant comfort.[113] Encycle's technology is used by warehouses, libraries, offices, food processing plants, and light industrial centers.[114]

SWARM LOGIC

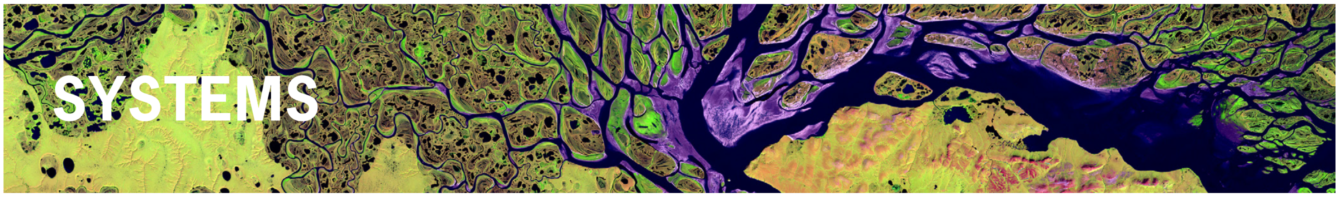
Altair, a Michigan-based technology company, uses the principles of evolution in their OptiStruct software, which was created to help customers optimize the weight and strength of a design. In addition to using evolutionary algorithms to analyze mechanical stresses in a design, the software mimics the logic underlying the way bones thicken in response to stress. OptiStruct's evolutionary algorithm rapidly tests a wide range of possible iterations to find the optimal balance between weight, strength, and ease of manufacturing. The resulting structure is material-efficient and lightweight and requires far less human design time to produce.[115] OptiStruct has aided organizations like Honeywell, Boeing, The Scripps Research Institute, Unilever, Alfa Romeo, SOM, Lockheed Martin, and Hitachi.[116] In one case, OptiStruct reduced the total weight of an Airbus design by 20%.[117]

OPTISTRUCT® SOFTWARE

PRODUCTS IN DEVELOPMENT

The postage stamp-sized SyNAPSE chip, under development by IBM and Cornell Tech, performs 46 billion synaptic operations per second using only 1 watt. The neural network-inspired chip marks a major step towards the project's ultimate goal of building a 10 billion neuron, 100 trillion synapse chip that fits into a 2 liter volume and consumes only 4 kW. The current chip has significant advantages over conventional chips: each core only operates when needed, allowing it to run on the equivalent of a hearing-aid battery, and the distributed cores process independently, which improves performance. This low-power chip could advance cloud computing, home health monitoring, vision aids for the blind, and other multi-sensory data processing. IBM ultimately hopes to combine the sensory processing capacity of the SyNAPSE chip with existing computing architectures that excel at analytical processing.[118,119]

IBM SYNAPSE CHIP



SYSTEMS

An ecosystem is a complex, intricate system that processes materials, energy, and information, often cycling these constituents within and between subsystems. Through evolution, nature creates flourishing ecosystems that optimize material and energy use. A valuable characteristic of ecosystems is that they operate from nano- to macroscales, allowing materials and energy to be reused and transferred across scales. Intentionally mimicking these key characteristics and harmoniously connecting society's industrial processes, building operations, and urban infrastructure to natural systems offers a path to a prosperous and resilient future for our society.

INDUSTRIES

- *Agriculture*
- *Building Construction*
- *Building Systems*
- *Data Centers*
- *Financial Services*
- *Food Manufacturing*
- *Healthcare*
- *HVAC & Refrigeration*
- *Oil & Gas*
- *Power Generation, Distribution & Storage*
- *Software*
- *Telecommunication*
- *Transportation*
- *Utilities*
- *Warehouse & Distribution*
- *Waste Management*
- *Water Treatment*

SELECTED STRATEGIES

CYCLIC FLOWS

The concept of waste does not exist in nature. In an ecosystem, resources discarded by one organism or community are harnessed by another, establishing symbiotic, cyclic flows. This occurs from the cellular scale (e.g., bacteria) to the macroscale (e.g., forests) and can create countless niches for growth. In comparison, human systems typically generate large amounts of waste. However, industrial by-products can be minimized by forming an industrial symbiosis—exchanging waste materials and energy as valued commodities between industries. Similar to biological symbiosis, individual companies benefit from shared services and the exchange of resources in the resulting system, increasing profits and dramatically reducing environmental impacts.

INTERDEPENDENCE

Ecosystems provide a wealth of inspiration for systems thinking. They also influence and integrate with our human-constructed systems. Viewing humans and nature as interconnected parts of a larger system allows us to evaluate how industrial processes, agriculture, buildings, and cities function in relation to our relatively frugal and efficient counterparts in nature. To evaluate the efficacy of projects in the built environment, Terrapin is developing the Phoebe Framework.

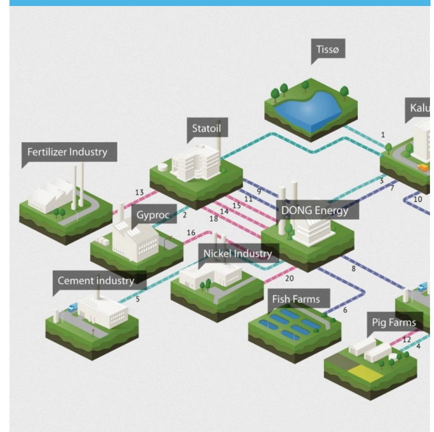
EMERGENCE

In a phenomenon known as emergence, complex systems have patterns and qualities that arise from the interactions among smaller components. Ecosystems exhibit many emergent properties, such as self-organization and adaptation, which can be incorporated into our engineered systems to address changing cultural, technical, and societal issues. Ecosystem services are another example of emergence, providing us with "services" such as food, water, fuel, disease control, and recreation. To continue to benefit from these services, human systems can look to restoration ecology, the Phoebe Framework, and other efforts to support the systems that produce them.

EXISTING PRODUCTS

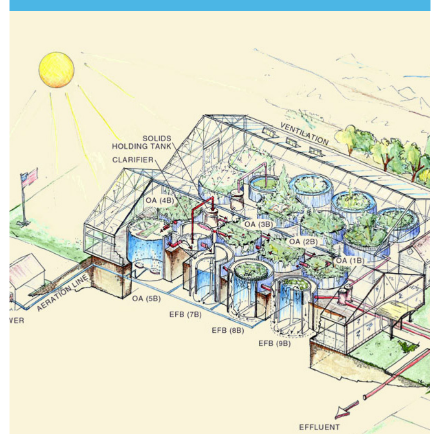
The industrial park of Kalundborg, Denmark, boasts a successful industrial symbiosis. Adjacent industrial facilities exchange resources and energy by-products so that one plant's waste becomes a feedstock for others. The sophisticated system currently includes a power plant, oil refinery, gypsum board manufacturer, biofuel producer, pharmaceutical manufacturer, fish and pig farms, fertilizer companies, cement companies, and the largest wastewater treatment plant in northern Europe, among other businesses. Some of the resources exchanged include fly ash, water, gas, fertilizer, and heat. Each year, Kalundborg's system avoids the emission of 240,000 tons of CO_2 and the use of 800 million gallons of water, saving an estimated $15 million. The Kalundborg Symbiosis organization aims to attract more industrial partners who are seeking to reduce their environmental impact and increase their profit margins.[120,121]

KALUNDBORG SYMBIOSIS



John Todd Ecological Design creates cost-effective wastewater treatment systems that harness the digestion and filtration functions of wetland ecosystems without using hazardous chemicals. Eco-Machine® systems consist of a series of tanks and water gardens housed in greenhouses or in constructed wetlands. Wastewater is filtered and polished by aquatic beds or constructed wetlands. The system contains all the major agents (bacteria, algae, snails, fungi, plants, fish, clams, etc.) of a wetland ecosystem. The Eco-Machines vary based on a project's climate, land area, and daily volume of wastewater.[122] An Eco-Machine installed at the Ethel M. Chocolates facility in Nevada treats all of its industrial wastewater (~32,000 gallons daily) and uses the filtered water to irrigate landscaping, eliminating the facility's municipal discharge fees while conserving water. The system is less expensive to build and operate than conventional treatment systems.[123]

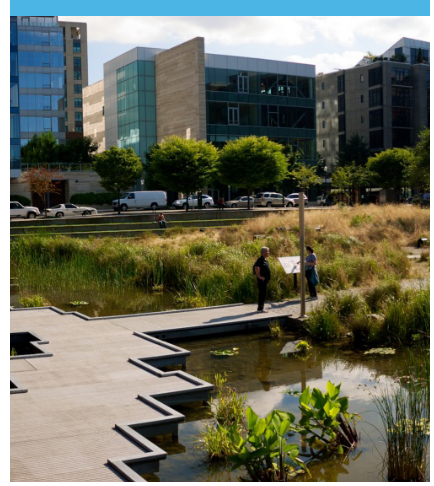
ECO-MACHINE®



PRODUCTS IN DEVELOPMENT

The Framework for an Ecological Built Environment ("Phoebe Framework" or "Phoebe") is a suite of tools in development at Terrapin that uses ecosystem-based assessment to guide sustainable and resilient development of buildings and communities. Phoebe merges sustainable design with environmental planning, industrial ecology, and restoration ecology, evaluating a site within its larger ecological context. Phoebe has three primary goals: connect humans to natural systems; establish ecological functions and processes on-site, aligning the built environment to regional ecosystems; and integrate larger ecosystem impacts into planning and decision making. Phoebe's advantage is that it does not adhere to universal metrics but crafts solutions tailored to a site's challenges. Using Phoebe restores local ecosystems, reduces a site's environmental impact and provides building owners and operators with opportunities to save money through risk mitigation, reduced resource consumption, and improved health and productivity.

PHOEBE FRAMEWORK



APPENDIX

DESCRIPTIONS FOR MARKET READINESS INFOGRAPHIC

Product	Description
CARBON	
Protein-Mediated Calcite Ceramics	Some organisms control calcite deposition to build complex structures like eggs–a process that could inspire precise ceramic manufacturing techniques.
Biomimetic Water-Splitting Catalyst	Terrapin assisted Dr. Dinolfo at RPI in securing funds for research that evaluates the rate and efficacy of an inexpensive catalyst. The catalyst mimics the water-splitting complex in plants and is used in artificialphotosynthetic devices, zinc-air batteries, and other oxidation-dependent systems.
Leaf-Mimicking Artificial Photosynthesis	Dr. Wan at RIT is developing a leaf-mimicking microfluidic device to convert CO_2 into valuable chemical products like methane and methanol. Terrapin helped secure funding for this project.
Photosynthetic Foam	Inspired by the tungara frog, which produces long-lasting foam nests, engineers at the University of Cincinnati developed a stable foam from one of the frog's proteins and combined it with photosynthetic enzymes that convert CO_2 to sugars and oxygen.
Enzymatic Toxin Remediation	Scientists at Georgia Tech patented the use of biological enzymes that break down harmful carbon compounds into valuable chemicals.
Blue Planet Green Building Materials	California-based Blue Planet synthesizes cement additives and other green building materials from waste carbon flue streams to make carbon-negative concrete. Terrapin is working with Blue Planet to identify potential demonstration sites in New York State.
Mango Materials	Using waste methane as a feedstock, Mango Materials grows bacteria that naturally produce a biopolymer. This economically competitive material can be used to create biodegradable plastic as well as conventional products like electronic casings, bottles, and children's toys.
BioWorld™ Oil Spill Bioremediation	Headquartered in California, BioWorld sells mixes of specialized bacteria that break down hydrocarbons into less harmful chemicals. These products are authorized by the EPA for use on oil spills.
Converge® Polyols	Novomer took inspiration from photosynthetic organisms and developed a process that sequesters carbon by converting waste CO_2 and CO into useful chemical polyerms. Currently, Ford is developing foams and plastics for its vehicles using the technology.
WATER	
Cactus-Inspired Fog Harvesting	The spines of the cactus *Opuntia microdasys* have specialized structures that can collect and funnel fog droplets into its base, prompting interest in fog harvesting devices that mimic the spines' structures.
Passive Fluid Transport	With potential applications in fields such as microfluidics, medical applications, and distilleries, this process of passively transporting fluid through interconnecting capillaries on a material's surface mimics the water retrieving process of Texas horned lizards' skin.

Affliation	Market Readiness	Industry Connections	Reference
Dr. Colin Freeman, University of Sheffield	Concept	Advanced Materials; Arts & Entertainment; Cement & Concrete	C. Freeman et al, "Structural control of crystal nuclei by an eggshell protein," *Angew. Chem. Int. Ed.*, vol. 49, Jun. 2010. doi: 10.1002/
Dr. Peter Dinolfo, RPI	Concept	Chemical Manufacturing; Oil & Gas; Optics & Imaging; Power Generation, Distribution & Storage; Transportation; Utilities	Personal communication with Dr. Dinolfo, 2014.
Dr. Jiandi Wan, RIT	Concept	Chemical Manufacturing; Oil & Gas; Optics & Imaging; Power Generation, Distribution & Storage; Transportation; Utilities	Personal communication with Dr. Wan, 2014.
Dr. David Wendell, University of Cincinnati	Concept	Advanced Materials; Oil & Gas; Power Generation, Distribution & Storage	D. Wendell et al, "Artificial photosynthesis in ranaspumin-2 based foam," *Nano Lett.*, vol. 10, Mar. 2010. doi: 10.1021/nl100550k.
Dr. Jim Spain, Georgia Tech	Prototype	Biotechnology; Chemical Manufacturing; Waste Management	"Biological materials," *Center for Biologically Inspired Design*, http://www.cbid.gatech.edu/, Accessed Dec. 2014.
Blue Planet Ltd.	Development	Building Construction; Cement & Concrete; Chemical Manufacturing; Mining; Paints & Adhesives	Personal communication with Blue Planet, 2014.
Mango Materials	Development	Advanced Materials; Biotechnology; Chemical Manufacturing; Oil & Gas; Plastic Products; Waste Management	"Mango Materials – Our Mission," Mango Materials, http://mangomaterials.com/, Accessed May 2016.
BioWorld™ Products	In Market	Biotechnology; Oil & Gas; Waste Management; Water Treatment	"Oil spill cleanup using bioremediation," *BioWorld Products*, http://www.bioworldusa.com/, Accessed Jan. 2015.
Novomer	In Market	Chemical Manufacturing; Household Goods; Oil & Gas; Plastic Products	Novomer, http://www.novomer.com/, Accessed Oct. 2014. "Preserving mother earth: Ford first automaker to use captured co2 to develop foam and plastic for vehicles," Ford Motor Company Media Center, https://media.ford.com/, Accessed August 2016.
Dr. Jie Ju & Dr. Hao Bai, Chinese Academy of Sciences	Concept	Agriculture; Water Treatment	J. Ju et al., "A multi-structural and multi-functional integrated fog collection system in cactus," *Nat Comms*, vol. 3, Dec. 2012. doi: 10.1038/ncomms2253.
Dr. Philip Comanns; Aachen University	Prototype	Advanced Materials; Agriculture; Building Systems; Food Manufacturing; Glass Products; HVAC & Refridgeration; Utilities	"Lizard's funnelling skin copied in the lab," BBC News, http://www.bbc.com/news/, Accessed May 2016.

Product	Description
Termite Humidity Damping Device	In collaboration with Terrapin Bright Green, Dr. Rupert Soar and Dr. Scott Turner are developing a passive humidity damping device based on the fungal combs in termite mounds. The device will stabilize humidity in building spaces, reducing a building's energy demands.
Fog Harvesting Mesh	Researchers at MIT and Pontifical Catholic University of Chile have designed specialized fog mesh nets that condense and capture 10% of the water in fog, a strategy inspired by how some Chilean organisms collect water from fog.
NBD Nano Hydrophobic Coatings	NBD Nano is developing a novel hydrophobic coating inspired by the Namibian Desert Beetle's shell. This coating for condensing tubes in power plants increases heat transfer rate by 200%, and has applications in other industrial processes, thermal desalination, and fog harvesting. NBD Nano is moving into large scale pilot testing.
Seawater Greenhouse	Inspired by the way the Namib beetle collects water from fog, Seawater Greenhouses use cold seawater, air movement, and solar radiation to condense and collect fresh water for crops.
Aquaporin Inside™	Aquaporin A/S is pilot testing a membrane system embedded with biological water channels that can filter water using 80% less energy than conventional processes.
Biolytix®	Biolytix markets a household wastewater treatment system that relies on worms and other organisms to filter water and break down sewage. The system uses no toxic chemicals and 90% less energy than conventional aerated sewage treatment systems.
MATERIALS	
Bacteria-Inspired Adhesive	The bacterium *Caulobacter crescentus* produces a biodegradable, waterproof adhesive with greater strain resistance than commercial super glues. Dr. Jay Tang at Brown University believes that mimicking its chemistry could yield a nontoxic glue that adheres underwater.
Spider Silk	Spider silk has high tensile strength, extensibility and toughness compared to synthetic fibers like Kevlar and nylon. Researchers are investigating how to produce similar fibers for extremely strong threads, cords, and cables.
Whale Pacemaker	Contractions in humpback whale hearts are controlled by nano-fibers that conduct electrical signals through an otherwise non-conductive grease coating the heart. Mimicking this concept using carbon nanowires could lead to a new type of pacemaker.
Keratin-Inspired Polymer Synthesis	Dr. Nomura at SUNY-ESF is producing low-embodied energy, keratin-inspired polymers to be used as crosslinking agents in resins and coatings, replacing petroleum-derived crosslinkers. Terrapin worked with the research team to find applications for the technology and secure funding.
Nacre-Inspired Deformable Glass	Inspired by the microscopic structure of nacre and teeth, researchers at McGill University developed deformable glass that is 200 times tougher than standard glass due to a pattern of micro-cracks.
Biofilm-Based Technology	Researchers at Harvard's Wyss Institute are expanding modified biofilms into a materials platform, with applications in nanoelectronics, industrial biocatalysis, optically active biological coatings, microbial fuel cells, and bioremediation.

Affliation	Market Readiness	Industry Connections	Reference
Terrapin Bright Green; Dr. Rupert Soar, Freeform Construction Ltd.; Dr. Scott Turner, SUNY-ESF	Prototype	Building System; HVAC & Refrigeration	Personal communication with Dr. Soar and Dr. Turner, 2014.
MIT and Pontifical Catholic University of Chile	Development	Agriculture; Food Manufacturing; Water Treatment	D. Chandler, "How to get fresh water out of thin air," *MIT News*, Aug. 2013, http://newsoffice.mit.edu/, Accessed Dec. 2014.
NBD Nanotechnologies, Inc.	Development	Advanced Materials; Agriculture; HVAC & Refrigeration; Industrial Machinery; Power Generation, Distribution & Storage; Water Treatment	NBD Nano, http://www.nbdnano.com/index.html, Accessed Mar 2015.
Seawater Greenhouses Ltd.; Sundrop Farms Pty. Ltd.	Development	Agriculture; Chemical Manufacturing; Water Treatment	T. McKeag. "Case Study Sahara Forest Project: Seeing the Forest for the Trees." *Zygote Quarterly*, vol. 4, 2014, Accessed Nov. 2014.
Aquaporin A/S	In Market	Biotechnology; Power Generation, Distribution & Storage; Water Treatment	"Biomimetic membranes - New separation technology tools with ancient roots," *Aquaporin*, http://www.aquaporin.dk/, Accessed Oct. 2014.
Biolytix	In Market	Waste Management; Water Treatment	"Biolytix ... Award winning wastewater treatment systems," *Biolytix*, http://www.biolytix.com/, Accessed Nov. 2014.
Dr. Jay Tang, Brown University	Concept	Advanced Materials; Paints & Adhesives	E. Ternaux et al., *Industry of nature: Another approach to ecology*, Frame Publishers, 2010.
Multiple Researchers	Concept	Advanced Materials; Fibers & Filaments	C. Hayashi, "The magnificence of spider silk," *TED2010*, Feb. 2010, http://www.ted.com/, Accessed Feb. 2015.
Jorge Reynolds Pombo	Concept	Biotechnology; Electronics; Fibers & Filaments; Healthcare; Pharmaceuticals	E. Ternaux et al., *Industry of nature: Another approach to ecology*, Frame Publishers, 2010.
Dr. Chris Nomura, SUNY-ESF	Concept	Chemical Manufacturing; Oil & Gas; Plastic Products	Personal communication with Dr. Nomura, 2014.
Dr. Francois Barthelat, McGill University	Concept	Advanced Materials; Glass Products	R. Tesfaye, "How seashells inspired 'unbreakable' glass," *The McGill Daily*, Feb. 2015, http://www.mcgilldaily.com/, Accessed Feb. 2015.
Dr. Neel Joshi, Harvard University	Prototype	Advanced Materials; Biotechnology; Chemical Manufacturing; Electronics; Optics & Imaging; Power Generation, Distribution & Storage; Waste Management	"Biofilm engineering," *The Joshi Lab*, http://www.joshigroup.seas.harvard.edu/, Accessed Nov. 2014.

Product	Description
Enzyme-Inspired Polymer Synthesis	At Cornell University, Dr. Geoff Coates is developing an enzyme-like catalyst to synthesize biodegradable polyesters produced using significantly less energy than conventional polyester. Terrapin worked closely with Dr. Coates to develop research proposals and secure funding.
Lotus Leaf-Inspired Coating	With assistance from Terrapin, Cornell researcher Dr. Anil Netravali is developing a superhydrophobic coating for high voltage power lines that reduces ice buildup, electrical outages, and costly infrastructure damage during winter storms.
Mussel-Inspired Adhesive	At RPI, Dr. Rich Gross is synthesizing cost-effective, environmentally-friendly bioadhesives designed by mimicking the chemical and mechanistic features of marine mussels' byssal threads. Terrapin worked with Dr. Gross to differentiate his technology from competitors and secure funding.
Squid-Inspired Self-Healing Polymer	Inspired by the mechanical properties of squid teeth, engineers created a polymer that can heal itself in the presence of warm water and slight pressure. This product may be applied in medical implants, textiles, cosmetics, and other applications where self-healing polymers are valuable.
BioKnit Shoes	Similar to the strategy seen in many organisms where a limited number of substances are specifically used to produce materials with diverse mechanical properties, the shoe's manufacturing process uses a single material to create a recyclable shoe that features varying levels of softness, strength, and flexibility.
Landesgartenschau Exhibition Hall	Taking inspiration from the material-efficient structures of organisms like sand dollars, architect Achim Menges constructed a bubble-like pavilion using interlocking timber panels.
Modern Meadow Meat	Modern Meadow is using tissue engineering techniques that prompt animal cells to grow into muscle tissue for meat. This system provides an alternative to environmentally-destructive animal farming.
Tree-Inspired Superwicking Materials	Dr. Chunlei Guo at University of Rochester uses laser processing to produce superwicking materials that enable more efficient air conditioning. Terrapin worked with Dr. Guo to define the market value of his technology and secure funding.
Worm-Inspired Surgical Glue	Researchers at the Karp Lab in Cambridge, Massachusetts, are developing a sandcastle worm-inspired surgical glue that sets while inside organs.
Modern Meadow Leather	Biotech startup Modern Meadow uses advanced tissue engineering techniques to make lab-grown leather that is analogous to leather produced from animals.
SLIPS	Inspired by the slippery surface of the pitcher plant, this microscopic coating has applications in anti-fouling, heat exchange ,and rapid defrosting. SLIPS Technologies was launched in 2014 after incubation at Harvard's Wyss Institute.
Bioinspired Hierarchical Structures	R&D firm Ceralink uses laminated object manufacturing, a rapid prototyping technique, to replicate bioinspired structures for use in clean energy applications. Terrapin worked with Ceralink to secure early-stage funding.
Engineered Silk	Inspired by spider silk, Bolt Threads spins yeast-produced proteins into silk. These fibers–made from water, sugar, and salts–can provide garments and fabrics with greater durability and strength. The company raised $50 million in its Series C funding round

Affliation	Market Readiness	Industry Connections	Reference
Dr. Geoff Coates, Cornell University	Prototype	Chemical Manufacturing; Oil & Gas; Plastic Products	Personal communication with Dr. Coates, 2014.
Dr. Anil Netravali, Cornell University	Prototype	Advanced Materials; Chemical Manufacturing; Paints & Adhesives; Power Generation, Distribution & Storage; Utilities	Personal communication with Dr. Netravali, 2014.
Dr. Rich Gross, SyntheZyme	Prototype	Advanced Materials; Paints & Adhesives	Personal communication with Dr. Gross, 2014.
Dr. Melik Demirel; Penn State	Prototype	Advanced Materials; Biotechnology; Fibers & Filaments; Pharmaceuticals; Plastic Products; Telecommunications; Textiles & Apparel	"Super-strong material inspired by squid teeth is self-healing," Popular Science, http://www.popsci.com/, Accessed May 2016.
Ammo Liao Design	Prototype	Advanced Materials; Fibers & Filaments; Textiles & Apparel	"BioKnit: A New Type of Shoe," Circulate News, http://circulatenews.org/, Accessed May 2016.
Achim Menges, University of Stuttgart	Prototype	Arts & Entertainment; Building Construction; Wood Products	A. Menges, "Landesgartenschau exhibition hall," *Stuttgart University*, 2014, http://www.achimmenges.net/, Accessed Dec. 2014.
Modern Meadow, Inc.	Prototype	Agriculture; Biotechnology; Food Manufacturing	A. Forgacs, "Leather and meat without killing animals," *TEDGlobal 2013*, Jun. 2013, http://www.ted.com/, Accessed Jan. 2015.
Dr. Chunlei Guo, University of Rochester	Prototype	Advanced Materials; Building Systems; HVAC & Refrigeration; Metal Manufacturing; Plastic Products	Personal communication with Dr. Guo, 2014.
Dr. Jeffrey Karp, Brigham and Women's Hospital	Prototype	Biotechnology; Healthcare; Paints & Adhesives; Pharmaceuticals	N. Lang et al., "A blood-resistant surgical glue for minimally invasive repair of vessels and heartdefects," *Sci. Transl. Med.*, vol. 6, Jan. 2014. DOI: 10.1126/ citranslmed.3006557.
Modern Meadow, Inc.	Development	Agriculture; Biotechnology; Textiles & Apparel	A. Forgacs, "Leather and meat without killing animals," *TEDGlobal 2013*, Jun. 2013, http://www.ted.com/, Accessed Jan. 2015.
SLIPS Technologies, Inc.	Development	Advanced Materials; Glass Products; Healthcare; Paints & Adhesives	"About SLIPS," *SLIPS Technologies*, 2014, http://www.slipstechnologies.com/, Accessed Feb. 2015.
Ceralink, Inc.	Development	Advanced Materials; Industrial Machinery; Power Generation, Distribution & Storage	Personal communication with Ceralink, 2014.
Bolt Threads	Development	Advanced Materials; Biotechnology; Chemical Manufacturing; Fibers & Filaments; Textiles & Apparel	"Bolt Threads – Technology," Bolt Threads, https://boltthreads.com/, Accessed May 2016.

Product	Description
Shrimp-Inspired Composite Material	The developers of this highly impact-resistant composite material—inspired by the hard club of the Mantis shrimp—received an acquisition offer that provided initial seed investors a 10x return in only 18 months.
Biocement™ Bricks	Combining sand, bacteria, nutrients, a nitrogen source, a calcium source, and water, biotech startup bioMASON "grows" bricks by leveraging the bacteria's metabolic activities, which cause calcium carbonate to cement the sand together without firing. The company has begun licensing their technology for manufacturing bricks on-site.
Gingko Bioworks	Ginkgo uses microbes to grow valuable products. The microorganisms are modified by introducing DNA sequences known to produce industry-relevant materials. The company has focused on sectors including "flavors and fragrance, cosmetics and personal care, and food and nutrition" and recently raised $100 million in Series C funding.
Greenshield®	This nanoparticle-based textile finish, inspired by plant leaves, allows water droplets to roll off fabric, carrying along dirt and other particles to create a self-cleaning effect.
Mother Dirt™	This body spray contains bacteria that convert urea and ammonia in sweat—which is abrasive to the skin, causing acne and irritation—into nitrite, which has anti-inflammatory properties. The spray reduces a user's dependence on modern hygiene products and replenishes the skin microbiome.
Mushroom® Materials	Ecovative grows mycelium in molds filled with agricultural waste. The fungi bind the waste fibers together into a solid mass, which is heat treated to produce a biodegradable alternative to harmful synthetic packaging and other products.
Sharklet™	Sharklet™ surface textures are used on products like medical devices, furniture, and cell phone cases. The plastic coatings have microscopic patterns inspired by sharkskin that repel bacteria without perpetuating antibiotic resistance.
WikiPearls™	Inspired by fruit and vegetable peels, WikiPearls™, developed by WikiFoods, Inc., seal food and beverages in bite-sized, edible "wrappers" that obviate plastic packaging.
Harprint®	This hair treatment, currently designed for brown or black hair, restores gray hair to its former color. The technology mimics the hair pigmentation process and uses the natural pigment eumelanin that dictates hair color.
Interface® Carpet	Global carpet manufacturer Interface developed modular carpet tiles with patterns that can be laid down randomly, without glue, mimicking variegated leaves on a forest floor.
StoCoat Lotusan®	Building products manufacturer Sto Corp. developed a hydrophobic acrylic paint that mimics the self-cleaning properties of the lotus leaf.
PureBond®	Developed by Columbia Forest Products, this soy-based glue mimics mussel adhesive. The North American panel manufacturer uses PureBond to laminate plywood without added formaldehyde.
VELCRO® Fasteners	This ubiquitous fastener, invented by George de Mestral, was inspired by the miniature hooks on seed burrs that allow them to cling to looped fabric.
ENERGY CONVERSION & STORAGE	
Ear Protein-Inspired Power	The prestin protein in animal ears converts vibrations into electrical signals. IntAct Labs, now Cambrian Innovation, embedded prestin proteins into "skins" that generate electricity from movement and wind.

Affliation	Market Readiness	Industry Connections	Reference
Nature Inspired Industries; Dr. David Kisailus (UC Riverside)	Development	Advanced Materials; Cement & Concrete; Fibers & Filaments; Paints & Adhesives; Plastic Products	S. Nealon, “Mantis shrimp stronger than airplanes: Composite material inspired by shrimp stronger than standard used in airplane frames,” *University of California/ Science Daily*, Apr. 2014, http://www.sciencedaily.com/, Accessed Nov. 2014. Personal communication, 2016.
bioMASON	In Market	Advanced Materials; Biotechnology; Building Construction; Cement & Concrete	“bioMASON GrowsBricks,” *bioMASON*, http://biomason.com/, Accessed Jan. 2015.
Gingko Bioworks	In Market	Biotechnology; Chemical Manufacturing; Food Manufacturing; Healthcare; Household Goods; Pharmaceuticals	http://ginkgobioworks.com, Accessed August 2016.
BigSky Technologies	In Market	Advanced Materials; Fibers & Filaments; Household Goods, Textiles & Apparel	“The first and only textile finish inspired by nature,” GreenShield, http://greenshieldfinish.com/, Accessed May 2016.
AOBiome	In Market	Biotechnology; Healthcare; Household Goods; Pharmaceuticals	C. Winter, “The Bacteria Solution,” Bloomberg Businessweek, Jul. 2015.
Ecovative	In Market	Advanced Materials; Agriculture; Biotechnology; Building Construction; Plastic Products; Waste Management	“Mushroom Materials,” *Ecovative Design*, http://www.ecovativedesign.com/, Accessed Feb. 2015.
Sharklet Technologies, Inc.	In Market	Advanced Materials; Healthcare; Paints & Adhesives; Plastic Products	Terrapin Bright Green. “Non-toxic anti-fouling solutions: Sharklet,” *New York Biomimicry Innovators Group*, http://www.ny-big.org/, Accessed Oct. 2014.
WikiFoods, Inc.	In Market	Advanced Materials; Food Manufacturing; Waste Management	“wikipearl™,” *WikiFoods, Inc.*, 2014, http://www.wikipearl.com/, Accessed Dec. 2014.
Hairprint; Warner Babcock Institute	In Market	Healthcase; Household Goods; Pharmaceuticals	“Hairprint – Restores your hair to its natural color,” Hairprint, http://www.myhairprint.com/, Accessed May 2016.
Interface, Inc.	In Market	Household Goods; Textiles & Apparel	“Innovations,” *Interface*, http://www.interface.com/, Accessed Jan. 2015.
Sto Corp.	In Market	Advanced Materials; Paints & Adhesives	“StoCoat Lotusan,” *Sto Corp.*, http://www.stocorp.com/, Accessed Jan. 2015.
Columbia Forest Products	In Market	Chemical Manufacturing; Paints & Adhesives; Wood Products	Terrapin Bright Green. “Healthy and cost-effective indoor environments: Purebond,” *New York Biomimicry Innovators Group*, http://www.ny-big.org/, Accessed Jan. 2015.
Velcro Industries	In Market	Textiles & Apparel	“About us,” *Velcro*, http://www.velcro.com/, Accessed Jan. 2015.
Cambrian Innovation	Concept	Advanced Materials; Building System; Electronics; Power Generation, Distribution & Storage	M. Silver and K. Vistakula, “Bio-electric space exploration,” *IntAct Labs LLC*, May 2007.

Product	Description
Red Panda Biofuel Enzymes	Terrapin helped secure early funding for research by Dr. Stipanovic at SUNY-ESF. He aims to isolate the digestive enzymes of Red Pandas – which efficiently convert biomass to fermentable sugars – for use in biofuel production.
Electric Eel BattCell	Advanced Biomimetic Sensors claims that their patented BattCell prototype, inspired by the electric eel, uses a biomimetic membrane to enhance its power density beyond other fuel cell technologies.
bioSTREAM™ Power	BioPower Systems in Australia is developing fishtail-inspired modules that generate power from tidal currents. The fin of each module pivots relative to the direction of the current, creating a swimming motion that generates an electric current.
µMist® Platform	Licensed to Swedish Biomimetics 3000, µMist® Platform Technology mimics the high velocity spray valve of the Bombardier Beetle to vaporize liquids using lower pressure than conventional systems. µMist could lead to more efficient combustion engines.
bioWAVE™ Power	bioWAVE™, a wave energy generator developed by BioPower Systems, mimics the motion of ocean vegetation. The swaying motion generates power through a unique hydraulic system undergoing testing in a 250 kW demonstration project.
Pilus Cell™	Ohio-based Pilus Energy, a subsidiary of Tauriga Sciences, is currently pilot testing its microbial fuel cell technology. As modified bacteria break down organics in wastewater, they produce electricity, treated water, and useful chemical compounds.
Voltaic Pile	Studies of the electric Torpedo ray and frog leg nerve responses led Alessandro Volta to build the first battery, the Voltaic pile, by stacking metal and salt-soaked discs in a similar arrangement to the discs within the fish's electric organ.
OPTICS & PHOTONICS	
Sea Sponge Glass Fibers	Highly fracture-resistant sea sponge spinacles could inspire tougher optical glass fibers manufactured at room temperature.
Spider Web-Based Optoelectronics	Metallized spider webs perform better than standard optoelectronic arrays and can be stretched without losing performance. This finding by several academic teams paves the way to next-generation flexible touch screens.
Moth Eye-Inspired X-Ray Imaging	Researchers found that a radial microstructure inspired by moth eyes increases light extraction of X-ray machine scintillators. This finding may enable lower dose radiation for imaging patients.
Beetle Shell-Inspired Humidity Sensor	Scientists at Sogang University have developed a microporous material inspired by the shell of the Hercules beetle that changes color in response to humidity levels. This material could be used in a low-power humidity sensor.
Cephalopod Skin-Inspired Displays	Inspired by cephalopods, researchers at the Eugene Bell Center in Massachusetts are creating electronic-sensing and color changing sheets. These optical materials may be used in low-power electronic displays.
Seed-Inspired Color Changing Fibers	After studying the photonic properties of the Margaritaria nobilius seed, researchers at MIT developed fibers that change color when stretched.

Affliation	Market Readiness	Industry Connections	Reference
Dr. Art Stipanovic, SUNY-ESF	Concept	Agriculture; Biotechnology; Oil & Gas; Power Generation, Distribution & Storage; Waste Management	Personal communication with Dr. Stipanovic, 2014.
Advanced Biomimetic Sensors, Inc.	Prototype	Advanced Materials; Electronics; Power Generation, Distribution & Storage	"Our developmental products," *Advanced Biomimetic Sensors*, 2009, http://abs-isensors.com/, Accessed Nov. 2014.
BioPower Systems	Prototype	Power Generation, Distribution & Storage; Industrial Machinery; Utilities	"bioSTREAM," *BioPower Systems*, http://www.biopowersystems.com/, Accessed Dec. 2014.
Swedish Biomimetics 3000 Ltd.	Development	Chemical Manufacturing; Food Manufacturing; HVAC & Refrigeration; Oil & Gas; Paints & Adhesives; Power Generation, Distribution & Storage; Transportation; Water Treatment	"Current technologies: µMist® Platform Technology," *Swedish Biomimetics 3000*, 2013, http://www.swedishbiomimetics.com/, Accessed Feb. 2013.
BioPower Systems	Development	Industrial Machinery; Power Generation, Distribution & Storage; Utilities	"bioWAVE," *BioPower Systems*, http://www.biopowersystems.com/, Accessed Dec. 2014.
Pilus Energy	Development	Biotechnology; Chemical Manufacturing; Power Generation, Distribution & Storage; Water Treatment	Pilus Energy/YouTube, "Pilus Energy is going to save the world…," *YouTube*, Jan. 2014, https://www.youtube.com/, Accessed Jan. 2015.
Alessandro Volta	In Market	Chemical Manufacturing; Electronics; Power Generation, Distribution & Storage	S. Finger and M. Piccolino, *The shocking history of electric fishes: From ancient epochs to the birth of modern neurophysiology*, Oxford University Press, 2011.
Dr. Joanna Aizenberg, Harvard University	Concept	Advanced Materials; Glass Products; Lighting; Optics & Imaging; Telecommunications	J. Aizenburg et al., "Biological glass fibers: Correlation between optical and structural properties," *PNAS*, vol. 101, Mar. 2004. doi: 10.1073/pnas.0307843101.
Dr. Jinwei Gao, South China Normal University	Concept	Electronics; Optics & Imaging	B. Han et al., "Bio-inspired networks for optoelectronic applications," *Nat. Comms.*, vol. 5, Nov. 2014. doi:10.1038/ncomms6674.
Dr. Yasha Yi-a, City University of New York	Concept	Advanced Materials; Healthcare; Optics & Imaging	"Bugs inspire better x-rays: Nanostructures modeled like moth eyes may boost medical imaging," *Optical Society of America/ Science Daily*, Jul. 2012, http://www.sciencedaily.com/, Accessed Nov. 2014.
Dr. Seung-Yop Lee and Dr. Jungyul Park, Sogang University	Prototype	Advanced Materials; Electronics; Optics & Imaging	JH Kim et al., "Biologically inspired humidity sensor based on three-dimensional photonic crystals," *Appl Phys Lett*, vol. 97, Sep. 2010. DOI: 10.1063/1.3486115.
Dr. Roger Hanlon, Marine Biological Laboratory	Prototype	Advanced Materials; Electronics; Optics & Imaging	C. Yu et al., "Adaptive optoelectronic camouflage systems with designs inspired by cephalopod skins," *PNAS*, vol. 111, Sept. 2014. doi: 10.1073/pnas.1410494111.
Dr. Mathias Kolle, MIT	Prototype	Advanced Materials; Fibers & Filaments; Optics & Imaging	M. Kolle et al., "Bio-inspired band-gap tunable elastic optical multilayer fibers," *Adv Matr*, vol. 25, Jan. 2013. doi: 10.1002/adma.201203529.

Product	Description
Butterfly-Inspired IR Sensor	GE Global Research is using Morpho butterfly wing scale microstructures as inspiration for small, highly sensitive infrared sensors.
ChromaFlair® Paint	JDSU, a manufacturer based in California, makes brilliant, color-shifting paints that use the thin-film interference phenomenon found in butterfly wings and seashells. The company's ChromaFlair® paint is used on cars, sports equipment, and building interiors.
Dye-Sensitized Solar Cells	Dyesol's dye-sensitized solar cells, which mimic the electron transport chain in photosynthesis, are printed on thin, flexible plastic using non-toxic, low-energy manufacturing.
IRLens™	Schaefer Ventilation's HotZone® Radiant Heaters rely on a lobster eye-inspired lens that focuses infrared radiation, heating a concentrated area instead of diffusing heat like standard radiant heaters.
Moth-Eye Anti-Reflective Film	Anti-reflective films inspired by the moth eye's microstructure improve solar cell photon absorption by 5 to 10%.
ORNILUX Glass	After studying how birds in flight avoid spider webs, the Arnold Glas Group in California commercialized ORNILUX, a spider web-patterned UV reflective glass that reduces bird collisions by 77%.
THERMOREGULATION	
Tardigrade-Inspired Organ Preservation	Studying how tardigrades and other organisms undergo anhydrobiosis, or extreme desiccation, could lead to better preservation of organs for transplant.
Vascular Window Cooling	Researchers at Harvard's Wyss Institute have created windows with microfluidic channels patterned like vascular circulatory systems.
HydRIS® Dry Vaccines	"Dry" vaccines, created by Nova Labs in the U.K., do not require refrigeration. The active materials are encased in a sugar matrix, a technique inspired by organisms that undergo anhydrobiosis, or extreme desiccation.
Leaf-Inspired Injection Molds	Plastics manufacturer HARBEC incorporated internal cooling channels in its molds, mimicking the flow patterns in dicot leaves, to dissipate heat more effectively. The new molds reduce cooling time and energy consumption by more than 20%. The increase in production speed has allowed HARBEC to fulfill tighter turn-around times.
SampleMatrix®	The California-based company Biomatrica developed processes akin to anhydrobiosis, or extreme desiccation, to stabilize fragile biological materials like DNA so they can be stored without refrigeration.
Arctic Fish-Inspired Ice Cream	Unilever developed a creamier, low-fat ice cream by adding an ice-structuring protein adopted from an arctic fish. The protein prevents large ice crystals from forming.

Affliation	Market Readiness	Industry Connections	Reference
Dr. Radislav Potyrailo, GE Global Research	Development	Advanced Materials; Building Systems; Data Centers; Optics & Imaging	A. Pris et al., "Towards high-speed imaging of infrared photons with bio-inspired nanoarchitectures," *Nat Photonics*, vol. 6, Feb. 2012. doi:10.1038/nphoton.2011.355.
JDSU	In Market	Advanced Materials; Arts & Entertainment; Paints & Adhesives	"ChromaFlair Pigment," *JDSU*, http://www.jdsu.com/, Accessed Nov. 2014.
Dyesol	In Market	Advanced Materials; Paints & Adhesives; Power Generation, Distribution & Storage	"Advantages of dye solar cell technology," *Dyesol*, http://www.dyesol.com/, Accessed Dec. 2014.
Schaefer Ventilation	In Market	Building Systems; HVAC & Refrigeration; Lighting	"HotZone portable electric infrared heater," *Schaefer Ventilation*, http://www.schaeferfan.com/, Accessed Dec. 2014.
Multiple Researchers	In Market	Advanced Materials; Glass Products; Power Generation, Distribution & Storage	Takemura et al., "Absence of eye shine and tapetum in the heterogeneous eye of Anthocharis butterflies (Pieridae)," *J. Exp Biol.* doi: 10.1242/jeb.002725 Yamada et al., "Characterization of antireflection moth-eye film on crystalline silicon photovoltaic module," *Opt Express*. doi: 10.1364/OE.19.00A118 Sun et al., "Broadband moth-eye antireflection coatings on silicon," *Appl Phy Lett*. doi: 10.1063/1.2870080
Arnold Glas	In Market	Building Systems; Glass Products	H. Ley, "Experimentelle Tests zur Wahrnehmbarkeit von UV-reflektierenden 'Vogelschutzgläsern' durch mitteleuropäische Singvögel," *Berichte zum Vogelschutz*, vol. 46, 2006.
Multiple Researchers	Concept	Biotechnology; Food Manufacturing; Healthcare	E. Ternaux et al., *Industry of nature: Another approach to ecology*, Frame Publishers, 2010.
Dr. Benjamin Hatton, Harvard University	Prototype	Building Systems; Glass Products; HVAC & Refrigeration	"Lifelike cooling for sunbaked windows," *Wyss Institute*, Jul. 2013, http://wyss.harvard.edu/, Accessed Jan. 2015.
Nova Laboratories Ltd.	In Market	Healthcare; HVAC & Refrigeration; Pharmaceuticals; Warehouse & Distribution	"HydRIS (Hypodermic Rehydration Injection System)," *Nova Laboratories Ltd*, http://www.novalabs.co.uk/, Accessed Dec. 2014.
Harbec, Inc.	Prototype	Industrial Machinery; Plastic Products	Personal communication with Harbec Plastics, 2014.
Biomatrica, Inc.	In Market	Healthcare; HVAC & Refrigeration; Pharmaceuticals; Warehouse & Distribution	V. Stern, "Dry out, put away," *The Scientist*, Feb. 2010, http://www.the-scientist.com/, Accessed Nov. 2014.
Unilever	In Market	Food Manufacturing	"Cool ice cream innovations," *Unilever*, http://www.unileverusa.com/, Accessed Jan. 2015.

Product	Description
FLUID DYNAMICS	
Cactus-Inspired High Rises	Inspired by the saguaro cactus, Dr. Letchford at RPI is studying the aerodynamics of vertically-grooved, slender cylinders to define optimal geometries for reduced wind loading on tall buildings.
Snake-Inspired Flight	The tree snake Chrysopelea glides from tree to tree by flattening its body and swaying in the air. DARPA funded research on Chrysopelea for possible military applications.
"V" Formation Flight	When moving through fluids, objects in a "V" formation expend less energy than solo objects.
Jellyfish Jet Propulsion	According to a research team at Caltech, jellyfish-inspired pulsed jet propulsion could be 50% more efficient that existing steady-jet propulsion.
RoboClam Excavator	A team at MIT constructed a prototype robotic excavator inspired by the low-drag burrowing of Atlantic razor clams. The excavator could be used for reversible ocean anchoring, subsea cable installation, and ocean sensor placement.
Schooling Fish Wind Farms	Engineers at Caltech developed algorithms inspired by schooling fish that decrease the amount of space required for vertical axis wind farms without compromising individual turbine efficiency.
Tubercle Technology™	Inspired by the tubercles found on whale fins, WhalePower developed blades with bumps along the leading edges that allow for very high stall angles. Envira-North Systems in Ontario applied the technology to their high volume, low speed Altra-Air fan.
500-Series Shinkansen Train	The Japanese bullet train has a pointed nose inspired by the kingfisher's beak that reduces noise and power consumption while increasing speed.
FE2owlet Fan	Inspired by the silent air movement over barn owl wings, the fan can improve the efficiency of air conditioners, refrigerators, and other ventilators by 15% while also reducing noise levels.
Lily Impeller	The form of the Lily Impeller, a highly efficient industrial mixer designed by PAX Scientific, was inspired by the aerodynamic shape of bird wings, rotating maple seeds, and other natural structures.
DATA & COMPUTING	
Bat-Nav System	Researchers at the Weizmann Institute in Israel found that bats track their positions in three dimensions using a donut-shaped coordinate system, which could inspire a new navigation system.
DNA-Based Computing	DNA-based computers could theoretically use chemical base pairs as "switches." This would enable a much more space-efficient, non-toxic form of computing that would pack the computing power of the most powerful supercomputer into a drop of water.
Venus Flytrap Electrical Switches	Trigger hairs inside the leaf of the carnivorous Venus flytrap act like electrical switches; when two are stimulated by an insect, the leaf closes. Such switches could inspire electrical devices made from abundant, non-toxic chemicals.

Affliation	Market Readiness	Industry Connections	Reference
Dr. Chris Letchford, RPI	Concept	Building Construction	Personal communication with Dr. Letchford, 2014.
Dr. Jake Socha, Virginia Tech	Concept	Transportation	"Flying snakes: Slithering through the air," *The Economist*, Dec. 2010, http://www.economist.com/, Accessed Dec. 2014.
Dr. Ilan Kroo, Stanford University	Concept	Oil & Gas; Transportation	"Efficient aviation: V for victory," *The Economist*, Dec. 2009, http://www.economist.com/, Accessed Dec. 2014.
Dr. John Dabiri, CalTech	Concept	Oil & Gas; Transportation	L. Ruiz et al., "Vortex-enhanced propulsion," *J. Fluid Mech.*, vol. 668, Dec. 2010. doi:10.1017/S0022112010004908.
Dr. Anette Hosoi, MIT	Prototype	Mining; Oil & Gas; Transportation	"RoboClam," MIT GEAR LAB, http://gear.mit.edu/, Accessed Dec. 2014.
Dr. John Dabiri, CalTech	Development	Power Generation, Distribution & Storage; Utilities	NU McCormick/YouTube, "Midwest mechanics seminar presents John Dabiri: Bio-inspired wind energy," *YouTube*, Nov. 2013, https://www.youtube.com/, Accessed Oct. 2014.
WhalePower	In Market	Building Systems; Data Centers; HVAC & Refrigeration; Power Generation, Distribution & Storage	Envira-North Systems Ltd, http://www.enviranorth.com/, Accessed Feb. 2015.
Eiji Nakatsu	In Market	Industrial Machinery; Transportation	E. Ternaux et al., *Industry of nature: Another approach to ecology*, Frame Publishers, 2010.
Ziehl-Abegg	In Market	Building Systems; Data Centers; Electronics; Food Manufacturing; HVAC & Refrigeration; Power Generation, Distribution & Storage; Utilities	"FE2owlet," Ziehl-Abegg, http://www.ziehl-abegg.com/us/en/, Accessed May 2016.
PAX Scientific	In Market	Building Systems; Cement & Concrete; Chemical Manufacturing; Data Centers; Electronics; Food Manufacturing; HVAC & Refrigeration; Power Generation, Distribution & Storage; Water Treatment	"PAX Mixer," *PAX Scientific*, http://paxscientific.com/, Accessed Feb. 2015.
Dr. Arseny Finklestein, Weizmann Institute of Science	Concept	Electronics; Software; Transportation	A. Abbott, "'Bat-nav' system enables three-dimensional manoeuvres," *Nature News*, Dec. 2014, http://www.nature.com/, Accessed Dec. 2014.
Multiple Researchers	Concept	Data Centers; Electronics; Software; Telecommunications	E. Ternaux et al., *Industry of nature: Another approach to ecology*, Frame Publishers, 2010.
Multiple Researchers	Concept	Advanced Materials; Biotechnology; Electronics	E. Ternaux et al., *Industry of nature: Another approach to ecology*, Frame Publishers, 2010.

Product	Description
Fibonacci Solar Power Plant	Fibonacci spirals are a naturally-occurring strategy for packing many units together efficiently. Engineers at MIT have modeled a Fibonacci sequence for reflectors in concentrated solar plants, creating an arrangement that would theoretically reduce land use by 20%.
Locust Collision Avoidance	Volvo is investigating how to incorporate the unique collision avoidance abilities of swarming locusts into crash avoidance sensors for cars.
Autonomous Robot Swarms	Autonomous robot swarms, developed by researchers at Harvard's Wyss Institute, organize themselves into complex shapes using swarm intelligence – a method of computation inspired by swarming organisms like ants, bees, birds, and bacteria.
DNA Data Storage	Scientists at Harvard's Wyss Institute coded 700 terabytes of data into less than one gram of DNA. The scientists believe that with further improvements, all the world's data (1.8 zettabytes) could theoretically be stored in about 4 grams of DNA.
Fly Ear Acoustic Sensor	Engineers at Michigan State developed a sensor based on a fly's ear that accurately detects the source of sounds using a mechanical lever system and neuronal signal processing.
Insect Eye Vision Sensor	Compound insect eyes can detect movement much faster than traditional cameras. This capacity has inspired novel vision sensors for aerial systems, robotics, high-speed inspection in manufacturing, and other applications.
Honey Bee Web Hosting	Researchers at Georgia Tech developed an internet server system that adapts to user demand the way bees adapt to changing food sources: by communicating the new locations back to the hive. The system increased one web hosting company's revenues by 20%.
IBM SyNAPSE Chip	Scientists at IBM and Cornell Tech developed a chip inspired by neural networks that increases performance during data-intensive computations and drastically reduces power consumption.
Ant-Based Distribution Algorithm	Bios Group, now NuTech Solutions, studied ant foraging to develop a logistics algorithm for industrial supplier Air Liquide. Air Liquide uses the algorithm to manage plant scheduling, weather, and deliveries, which has yielded substantial time and cost savings.
Artificial Immune System Software	Artificial immune systems are inspired by the way higher organism immune systems detect foreign bodies and adapt to rid the body of them. These algorithms are used in computer security, robotics, and fault detection.
Evolutionary-Designed Antenna	NASA contractors compared designs for a spacecraft antenna, one of which was developed using an evolutionary algorithm and the other using conventional engineering. The former outperformed the latter in functionality and reduced design time.
Ant-Based Plane Guidance	Southwest Airlines developed an ant-inspired computing algorithm that drastically reduces the amount of time planes wait for gates to open at airports.
OptiStruct® Structural Optimization	Inspired by the way bones grow, software developer Altair created structural analysis software that uses an evolutionary algorithm to find the optimum shape for components, reducing weight and materials without compromising strength.

Affliation	Market Readiness	Industry Connections	Reference
Dr. Corey Noone, MIT	Concept	Optics & Imaging; Power Generation, Distribution & Storage; Utilities	C. Noone, “Heliostat field optimization: A new computationally efficient model and biomimetic layout,” *Sol. Ener.*, vol. 86, Feb. 2012. doi:10.1016/j.solener.2011.12.007.
Volvo Car Group	Concept	Industrial Machinery; Software; Transportation	“Volvo cars turns to locust swarms for future safety solutions,” *Volvo Car Group*, Sept. 2008, https://www.media.volvocars.com/, Accessed Dec. 2014.
Dr. Radhika Nagpal, Harvard University	Prototype	Electronics; Industrial Machinery; Software	C. Perry, “A self-organizing thousand-robot swarm,” *Harvard School of Engineering and Applied Sciences*, Aug. 2014, http://www.seas.harvard.edu/, Accessed Dec. 2014.
Dr. George Church, Harvard University	Prototype	Advanced Materials; Data Centers; Electronics; Software	S. Anthony, “Harvard cracks DNA storage, crams 700 terabytes of data into a single gram,” *Extreme Tech*, Aug. 2012, http://www.extremetech.com/, Accessed Jan. 2015.
Dr. Shantanu Chakrabartty, Michigan State University	Prototype	Advanced Materials; Electronics; Industrial Machinery; Software; Telecommunication	T. Hino and S. Chakrabartty, “Chapter 14. Noise exploitation and adaptation in neuromorphic sensors,” *Engineered Biomimicry*, A. Lakhtakia, and R. Martín-Palma, Elsevier, 2013.
Multiple Researchers	Prototype	Electronics; Optics & Imaging; Software; Transportation	C.H.G. Wright and S. Barrett, “Chapter 1. Biomimetic vision sensors,” *Engineered Biomimicry*, A. Lakhtakia and R. Martín-Palma, Elsevier, 2013.
Dr. Craig Tovey, Georgia Tech	Development	Data Centers; Software; Telecommunications	B. Nelson, “Scientists abuzz over more efficient Web servers,” *NBC News.com*, Dec. 2007, http://www.nbcnews.com/, Accessed Jan. 2015.
IBM, Cornell Tech	Development	Data Centers; Electronics; Healthcare; Optics & Imaging; Software; Telecommunications; Transportation	“New IBM SyNAPSE Chip Could Open Era of Vast Neural Networks,” *IBM*, Aug. 2014, http://www.ibm.com/, Accessed Feb. 2015.
Nu Tech Software Solutions, Inc.	Development	Software; Transportation; Warehouse & Distribution	P. Miller, “The Genius of Swarms,” *National Geographic*, Jul. 2007, http://ngm.nationalgeographic.com/, Accessed Feb. 2015.
Multiple Researchers	Development	Biotechnology; Building Systems; Data Centers; Electronics; Financial Services; Healthcare; Software	E. Hart and J. Timmis, “Application areas of AIS: The past, the present and the future,” *Appl. Soft Comput.*, vol. 8, Dec. 2006. doi:10.1016/j.asoc.2006.12.004.
NASA	Development	Broadcast; Electronics; Industrial Machinery	G. Hornby et al., “Evolutionary computation,” *MIT Press J.*, vol. 19, Feb. 2011. doi:10.1162/EVCO_a_00005.
Southwest Airlines	In Market	Software; Transportation; Warehouse & Distribution	P. Miller, “The Genius of Swarms,” *National Geographic*, Jul. 2007, http://ngm.nationalgeographic.com/, Accessed Feb. 2015.
Altair	In Market	Building Construction; Industrial Machinery; Metal Manufacturing; Plastic Products; Software; Transportation	“Altair Optistruct: Optimization Driven Structural Analysis,” *Altair Hyperworks*, http://www.altairhyperworks.com/, Accessed Jan. 2015.

Product	Description
Swarm Logic™	Inspired by bee communication, Encycle's Swarm Logic™ systems reduce a building's energy draw, especially during peak hours, by using individual wireless controllers that coordinate when HVAC units power on.
SYSTEMS	
Sahara Forest Project	The Sahara Forest Project, proposed by British firm Exploration Architecture, combines evaporation from Seawater Greenhouses (see Water) with excess heat from adjacent concentrated solar plants in order to create moist microclimates that curb desertification.
Cardboard to Caviar	This closed-loop recycling scheme uses waste products like cardboard from restaurants to make products like caviar from farmed sturgeon. The concept could be replicated with other interrelated products to reduce waste and save energy and money.
Biomimetic Investing	Katherine Collins of Honeybee Capital proposed an investing framework that uses biological principles to encourage resilient, regenerative, and profitable investing activities.
Phoebe Framework	Created by Terrapin, the Framework for the Built Ecological Environment, or "Phoebe Framework," is a suite of tools that use ecosystem-based assessment to: connect humans to natural systems; establish ecological functions and processes on-site, aligning the built environment to regional ecosystems; and integrate larger ecosystem impacts into planning and decision making. Phoebe merges sustainable design with environmental planning, industrial ecology, and restoration ecology.
Aquaponic Systems	Hydroponics and fish farming are combined based on the symbiotic flow of nutrients between the fish and plants. Fish waste provides nutrients to the plants, which filter the water for the fish.
Eco-Machine®	John Todd Ecological Design uses constructed wetlands and aquatic tanks containing various microbes, plants, and aquatic animals to filter wastewater.
Kalundborg Industrial Symbiosis	In Kalundborg, Denmark, over 16 industrial facilities and farms in close proximity exchange materials and energy. One plant's waste becomes another's raw material, saving about $15 million a year.

Affliation	Market Readiness	Industry Connections	Reference
Encycle	In Market	Building Systems; Data Centers; HVAC & Refrigeration; Power Generation, Distribution & Storage; Software; Utilities	"Solutions - Demand Management," *Encycle*, http://www.regenenergy.com/, Accessed Feb. 2015.
Exploration Architecture	Concept	Agriculture; Power Generation, Distribution & Storage; Water Treatment	M. Pawlyn, *Biomimicry in architecture*, RIBA Publishing, 2011.
Graham Wiles	Prototype	Agriculture; Food Manufacturing; Waste Management	M. Pawlyn, *Biomimicry in architecture*, RIBA Publishing, 2011.
Honeybee Capital	Development	Financial Services	*Honeybee capital*, http://www.honeybeecapital.com/, Accessed Jan. 2015.
Terrapin Bright Green	Development	Agriculture; Building Construction; Building Systems; Food Manufacturing; Healthcare; Power Generation, Distribution & Storage; Utilities; Waste Management; Water Treatment	Terrapin Bright Green.
Multiple Companies	In Market	Agriculture; Waste Management; Water Treatment	E. Ternaux et al., *Industry of nature: Another approach to ecology*, Frame Publishers, 2010.
John Todd Ecological Design	In Market	Water Treatment	"About Eco-Machines," *John Todd Ecological Design*, http://toddecological.com/, Accessed Feb. 2015.
Kalundborg Symbiosis	In Market	Power Generation, Distribution & Storage; Utilities; Warehouses & Distribution; Waste Management; Water Treatment	"Kalundborg symbiosis," *Kalundborg Symbiosis Institute*, http://www.symbiosis.dk/en, Accessed Aug. 2012.

REFERENCES

1. J. Calvert et al., *Synthetic aesthetics: investigating synthetic biology's designs on nature,* MIT Press, 2014.
2. J. Benyus, *Biomimicry: Innovation inspired by nature*, HarperCollins Publishers, 1997.
3. E. G. Nisbet and N. H. Sleep, "The habitat and nature of early life," *Nature*, vol. 409, Feb. 2001. doi:10.1038/35059210
4. B. Wallace-Wells, "The Blip," *New York Magazine*, Jul. 2013, http://nymag.com/, Accessed Sept. 2014.
5. B. Kenny, "3 Ways to Innovate in a Stagnant Environment," *The Business*, Mar. 2014, Harvard Business School, http://www.hbs.edu/, Accessed Sept. 2014.
6. B. Gibney, "What happened to the future?" *Founders Fund*, 2011, http://www.foundersfund.com/, Accessed Sept. 2014.
7. "PRI Fact Sheet," *Principles for Responsible Investment*, http://www.unpri.org/news/, Accessed Mar. 2015.
8. S. Baker, "PRI exec harnessing the power of $45 trillion," *Pensions & Investments*, Oct. 2014, http://www.unpri.org/, Accessed Mar. 2015.
9. "Greenhouse Gas Emissions," EPA, Apr. 2014, http://www.epa.gov/, Accessed Oct. 2014.
10. "Clean Energy Fund Proposal," NYSERDA, 2014.
11. "Emissions," *Global carbon atlas*, 2014, http://www.globalcarbonatlas.org/, Accessed Oct. 2014.
12. "50 Disruptive Companies: Novomer," *MIT Technology Review*, 2012, http://www.technologyreview.com/, Accessed Oct. 2014.
13. "Chapter 11.6 Portland cement manufacturing," *Emission factors/AP 42*, vol. 1, EPA, Jan. 1995.
14. "2013 Activity Report," The European Cement Association, 2013.
15. Personal communication with Blue Planet, 2014.
16. E. Benhelal et al., "Global strategies and potentials to curb CO2 emissions in cement industry," *J. Clean Prod*, vol. 51, Jul. 2013. doi:10.1016/j.jclepro.2012.10.049
17. Novomer, http://www.novomer.com/, Accessed Oct. 2014.
18. C. J. Clouse, "How to Reduce Global Warming for Fun + Profit," *Ozy*, Oct. 2014, http://www.ozy.com/, Accessed Oct. 2014.
19. "Polymer produced from CO2 waste gas makes commercial debut," *Chemical Engineering*, Jan. 2015, http://www.chemengonline.com/, Accessed Feb. 2015.
20. J. Wan, "Research Interests," *WAN Microfluidic Laboratory*, https://www.rit.edu, Accessed Feb. 2015.
21. "Facts and figures," *UN Water*, 2013, http://www.unwater.org/, Accessed Dec. 2014.
22. S. Turner, "Fungi and water homeostasis," *Termite research*, http://www.esf.edu/, Accessed Oct. 2014.
23. J. Ju et al., "A multi-structural and multi-functional integrated fog collection system in cactus." *Nat Comms*, vol. 3, Dec. 2012. doi: 10.1038/ncomms2253.
24. T. Nørgaard, and M. Dacke, "Fog-basking behaviour and water collection efficiency in Namib Desert Darkling beetles," *Front Zool*, vol. 7, Jul. 2010. doi:10.1186/1742-9994-7-23.
25. J. Glime, "Ch. 7: Water relations: Physiological adaptations," *Bryophyte Ecol*, vol. 1, 2007, Accessed on Jan. 2015.
26. D. Chandler, "How to get fresh water out of thin air," *MIT News*, Aug. 2013, http://newsoffice.mit.edu/, Accessed Dec. 2014.
27. "Biomimetic membranes - New separation technology tools with ancient roots," *Aquaporin*, http://www.aquaporin.dk/, Accessed Oct. 2014.
28. "Invitation to join the water revolution," *Aquaporin*, http://www.aquaporin.dk/, Accessed Oct. 2014.
29. "News Archive," *Aquaporin Asia*, Oct. 2014, http://www.aquaporin.asia/, Accessed Oct. 2014.
30. T. McKeag. "Case Study Sahara Forest Project: Seeing the Forest for the Trees." *Zygote Quart*, vol. 4, 2014, Accessed Nov. 2014.
31. "Technology: Economics," *Seawater Greenhouse*, 2010, http://www.seawatergreenhouse.com/, Accessed Nov. 2014.
32. "Ventilation for Acceptable Indoor Air Quality," *ANSI/ASHRAE Standard 62.1-2013*, ASHRAE, 2013.
33. M. A. Meyer, and P. Chen, *Biological Materials Science*, Cambridge University Press, 2014.
34. T. McKeag, "Case study: Return of the swamp thing," *Zygote Quart*, vol. 3, 2012, Accessed Nov. 2014.
35. H. Bohn, and W. Federle, "Insect aquaplaning: Nepenthes pitcher plants capture prey with the peristome, a fully wettable water-lubricated anisotropic surface," *P. Natl Acad Sci USA*, vol. 101, Aug. 2004. doi: 10.1073/pnas.0405885101
36. K. Koch et al., "The superhydrophilic and superoleophilic leaf surface of Ruellia devosiana (Acanthaceae): a biological model for spreading of water and oil on surfaces," *Funct Plant Biol*, vol. 36, Apr. 2009. http://dx.doi.org/10.1071/FP08295.

37. “About SLIPS,” *SLIPS Technologies*, 2014, http://www.slipstechnologies.com/, Accessed Feb. 2015.
38. Terrapin Bright Green. “Non-toxic anti-fouling solutions: Sharklet,” *New York Biomimicry Innovators Group*, http://www.ny-big.org/, Accessed Oct. 2014.
39. H. Ensikat et al., “Superhydrophobicity in perfection: the outstanding properties of the lotus leaf,” Beilstein *J. Nanotechnol.*, vol. 2, Mar. 2011. doi:10.3762/bjnano.2.19.
40. “StoCoat Lotusan,” *Sto Corp.*, http://www.stocorp.com/, Accessed Jan. 2015.
41. “Mushroom Materials,” *Ecovative Design*, http://www.ecovativedesign.com/, Accessed Feb. 2015.
42. Grand View Research, “Grand View Research, Inc: Global adhesives and sealants market expected to reach USD 43,195.5 million by 2020,” Mar. 2014, http://www.grandviewresearch.com/, Accessed Jan. 2015.
43. Terrapin Bright Green. “Healthy and cost-effective indoor environments: Purebond,” *New York Biomimicry Innovators Group*, http://www.ny-big.org/, Accessed Jan. 2015.
44. Carbon War Room, “News bulletin: Brick making report - Reducing industry’s emissions through economic opportunity,” *Carbon War Room*, Jan. 2013, http://carbonwarroom.com/, Accessed Jan. 2015.
45. S. Lokier and G. K. Dosier, “A quantitative analysis of microbially-induced calcite precipitation employing artificial and naturally-occurring sediments,” *EGU General Assembly 2013*, vol. 15, 2013.
46. “bioMASON Grows Bricks,” *bioMASON*, http://biomason.com/, Accessed Jan. 2015.
47. “How to grow bricks from trillions of bacteria,” *WIRED Magazine*, Nov. 2015, http://www.wired.co.uk/, Accessed August 2016.
48. M. Mickhalaf et al., “Overcoming the brittleness of glass through bio-inspiration and micro-architecture,” *Nat Comms*, vol. 5, Jan. 2014. doi:10.1038/ncomms4166.
49. “Glass that bends but doesn’t break,” *McGill University*, Jan. 2014, http://www.mcgill.ca/, Accessed Feb. 2015.
50. R. Tesfaye, “How seashells inspired ‘unbreakable’ glass,” *The McGill Daily*, Feb. 2015, http://www.mcgilldaily.com/, Accessed Feb. 2015.
51. United Nations Food and Agriculture Organization, *Livestock’s Long Shadow*, 2006.
52. A. Forgacs, “Leather and meat without killing animals,” *TEDGlobal 2013*, Jun. 2013, http://www.ted.com/, Accessed Jan. 2015.
53. “Opportunity,” *Modern Meadow*, http://modernmeadow.com/, Accessed Feb. 2015.
54. P. Wilson et al., “Inhibition of ice nucleation by slippery liquid-infused porous surfaces (SLIPS),” *Phys Chem Chem Phys*, vol. 15, Nov. 2012. doi: 10.1039/C2CP43586A
55. T. Wong et al., “Bioinspired self-repairing slippery surfaces with pressure-stable omniphobicity,” *Nature*, vol. 477, Sept. 2011. doi:10.1038/nature10447
56. T. Iversen and A. Rommelhoff, “The starch statolith hypothesis and the interaction of amyloplasts and endoplasmic reticulum in root geotropism,” *J. Exp. Bot.*, vol. 29, Dec. 1978. doi: 10.1093/jxb/29.6.1319.
57. W. Martin et al., “Hydrothermal vents and the origin of life,” *Nat Rev Microbiol*, Sept. 2008. doi:10.1038/nrmicro1991
58. J. G. Holt, Ed. *Bergey’s Manual of Determinative Bacteriology*, Lippincott Williams & Wilkins, 1994.
59. “Energy,” *World Ocean Review*, 2010, http://worldoceanreview.com/, Accessed Feb. 2015.
60. “Ocean Energy,” *European Renewable Energy Association*.
61. Object: Austrailian Design Centre/YouTube, “Tim Finnigan on bioinspiration,” *YouTube*, Nov. 2012, https://www.youtube.com/, Accessed Dec. 2014.
62. “bioWAVE,” *BioPower Systems*, http://www.biopowersystems.com/, Accessed Dec. 2014.
63. “μMist spray technology,” *University of Leeds*, 2011, http://www.leeds.ac.uk/, Accessed Jan. 2015.
64. “Current technologies: μMist® Platform Technology,” *Swedish Biomimetics 3000*, 2013, http://www.swedishbiomimetics.com/, Accessed Feb. 2013.
65. N. Beheshti et al., “μMist®-The next generation fuel injection system: Improved atomisation and combustion for port-fuel-injected engines,” *SAE Intl*, Aug. 2011. doi: 10.4271/2011-01-1890
66. “Cosworth and Swedish Biomimetics 3000® announce technical partnership to advance fuel injection systems inspired by the bombardier beetle’s defence mechanism,” *Cosworth*, Jun. 2013, http://www.cosworth.com/, Accessed Jan. 2015.
67. “Beetle inspires development,” Medicon Village, Sept. 2012, http://www.mediconvillage.se/, Accessed Jan. 2015.
68. “Fact sheet: Energy production and efficiency research - The roadmap to net-zero energy” *Water Environment Research Foundation*, Aug. 2011.
69. Pilus Energy/YouTube, “Pilus Energy is going to save the world…,” *YouTube*, Jan. 2014, https://www.

youtube.com/ , Accessed Jan. 2015.

70. "Tauriga Sciences Inc. subsidiary Pilus Energy LLC receives approval from the US EPA to commence scaled up pilot test," *Nasdaq: Globe Newswire*, Sept. 2014, http://globenewswire.com/, Accessed Dec. 2014.

71. B. Phillips and P. Jiang, "Chapter 12. Biomimetic antireflection surfaces," *Engineered Biomimicry*, A. Lakhtakia and R. Martín-Palma, Elsevier, 2013.

72. L. Kuo-Huang et al., "Correlations between calcium oxalate crystals and photosynthetic activities in palisade cells of shade-adapted Peperomia glabella," *Bot Stud*, vol. 48, April 2007.

73. F. Chiadini et al., "Simulation and analysis of prismatic bioinspired compound lenses for solar cells: II. Multifrequency analysis," *Bioinspir & Biomim*, vol. 6, Mar. 2011. doi: 10.1088/1748-3182/6/1/014002.

74. Kolle, Mathias et al., "Bio-inspired band-gap tunable elastic optical multilayer fibers," *Adv Mater*, vol. 25, Jan. 2013. doi: 10.1002/adma.201203529.

75. R. Johnson, "Lens-like radiant energy transmission control means," U.S. Patent: 4896656 A, Jan. 1990.

76. C.H.G. Wright and S. Barrett, "Chapter 1. Biomimetic vision sensors," *Engineered Biomimicry*, A. Lakhtakia and R. Martín-Palma, Elsevier, 2013.

77. A.S. Risbud and M.H. Bartl, "Chapter 14. Solution-based Techniques for Biomimetics and Bioreplication," *Engineered Biomimicry*, A. Lakhtakia, and R. Martín-Palma, Elsevier, 2013.

78. N. Yamada et al., "Characterization of antireflection moth-eye film on crystalline silicon photovoltaic module," *Opt Express*, vol. 19, Jan. 2011. http://dx.doi.org/10.1364/OE.19.00A118.

79. W.J. Nam et al., "Incorporation of a light and carrier collection management nano-element array into superstrate a-Si:H solar cells," *Appl. Phys. Lett.*, vol. 99, Aug. 2011. doi: 10.1063/1.3628460.

80. K. Forberich et al., "Performance improvement of organic solar cells with moth eye anti-reflection coating," *Thin Solid Films*, vol. 516, Aug. 2008. doi:10.1016/j.tsf.2007.12.088.

81. A. Chutanin et al., "High-efficiency photonic crystal solar cell architecture," *Opt Express*, vol. 17, May 2009. http://dx.doi.org/10.1364/OE.17.008871.

82. S. Ritter, "How lobster eyes inspired a radiant heater," *Make*, Nov. 2014, http://makezine.com/, Accessed Jan. 2015.

83. "HotZone portable electric infrared heater," *Schaefer*, http://www.schaeferventilation.com/, Accessed Jan. 2015.

84. A. Pris et al., "Towards high-speed imaging of infrared photons with bio-inspired nanoarchitectures," *Nat Photonics*, vol. 6, Feb. 2012. doi:10.1038/nphoton.2011.355.

85. I. Mazzoleni, *Architecture Follows Nature*, CRC Press, 2013.

86. S. D'Amico et al., "Psychrophilic microorganisms: challenges for life," *EMBO Rep.*, vol. 7, April 2006, doi: 10.1038/sj.embor.7400662.

87. V. Bennett et al., "Comparative overwintering physiology of Alaska and Indiana populations of the beetle Cucujus clavipes (Fabricius): roles of antifreeze proteins, polyols, dehydration and diapause," *J Exp Bio*, vol. 208, Dec. 2005. doi: 10.1242/jeb.01892.

88. P.L. Davies and C.L. Hew, "Biochemistry of fish antifreeze proteins." *FASEB J*, vol. 4, May 1990.

89. J. Moskin, "Creamy, healthier ice cream? What's the catch?," *The New York Times*, Jul. 2006, http://www.nytimes.com/, Accessed Dec. 2014.

90. "Polymerase chain reaction (PCR)," *National Center for Biotechnology Information*, http://www.ncbi.nlm.nih.gov/, Accessed Nov. 2014.

91. C. Vieille and G.J. Zeikus, "Hyperthermophilic enzymes: Sources, uses, and molecular mechanisms for thermostability," *Microbiol Mol Biol Rev.*, vol. 65, Mar. 2001. doi: 10.1128/MMBR.65.1.1-43.2001.

92. C. Jaco Klok, "Anhydrobiosis," *Outside JEB*, 2010.

93. V. Stern, "Dry out, put away," *The Scientist*, Feb. 2010, http://www.the-scientist.com/, Accessed Nov. 2014.

94. D. Weaver et al., "Vaccine Storage and Handling," *Epidemiology and Prevention of Vaccine-Preventable Diseases*, W. Atkinson et al., Public Health Foundation, 2012.

95. "HydRIS (Hypodermic Rehydration Injection System)," *Nova Laboratories Ltd*, http://www.novalabs.co.uk/, Accessed Dec. 2014.

96. "Global - Ice Cream," *MarketLine*, Oct. 2014, http://store.marketline.com/, Accessed Jan. 2015

97. V. Gill, "Sub-zero proteins transform dessert," *BBC NEWS*, 15 Aug. 2009, http://www.bbc.com/, Accessed Jan. 2015.

98. "Cool ice cream innovations," *Unilever*, http://www.unileverusa.com/, Accessed Jan. 2015.

99. J. Harman, *The Shark's Paintbrush: Biomimicry and How Nature is Inspiring Innovation*, White Cloud Press: 2013.

100. A. Bejan and J. Zane, *Design in Nature: How the Constructal Law Governs Evolution in Biology, Physics, Technology, and Social Organization*, Doubleday,

2012.

101. “The PAX Water Mixer Advantage,” *PAX Water Technologies*, 2011, http://www.paxwater.com/, Accessed Dec. 2014.

102. “PAX Mixer,” *PAX Scientific*, http://paxscientific.com/, Accessed Feb. 2015.

103. N. Canter, “Humpback whales inspire new wind turbine technology,” *Tribology and Lubrication Technology*, Dec. 2008, http://www.stle.org/, Accessed Dec. 2014.

104. E*nvira-North Systems Ltd*, http://www.enviranorth.com/, Accessed Feb. 2015.

105. J. Dabiri, “Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays,” *J Renewable and Sustain Energy*, vol. 3,Jul. 2011. doi: 10.1063/1.3608170

106. A. Riley, “Fish School Us on Wind Power,” *Nautilus*, Jul. 2014, http://nautil.us/, Accessed Dec. 2014.

107. D. Floreano and C. Mattiussi, *Bio-inspired Artificial Intelligence: Theories, Methods and Technologies*, MIT Press, 2008.

108. P. Miller, “The Genius of Swarms,” *National Geographic*, Jul. 2007, http://ngm.nationalgeographic.com/, Accessed Feb. 2015.

109. M. Fischetti, “Computers versus Brains,” *Scientific American*, Oct. 2011.

110. S. Anthony, “Harvard cracks DNA storage, crams 700 terabytes of data into a single gram,” *ExtremeTech*, Aug. 2012, http://www.extremetech.comt/, Accessed Feb. 2015.

111. W. Banzhaf, “Chapter 17: Evolutionary Computation and Genetic Programming,” *Engineered Biomimicry*, A. Lakhtakia and R. Martín-Palma, Elsevier 2013.

112. “Solutions - Demand Management,” *Encycle*, http://www.regenenergy.com/, Accessed Feb. 2015.

113. “Innovative Paths To Energy Efficiency: REGEN Energy,” *New York Biomimicry Innovators Group*, http://www.ny-big.org/, Accessed Feb. 2015.

114. “Solutions - Markets Served,” *Encycle*, http://www.regenenergy.com/, Accessed Feb. 2015.

115. P. Patton, “Engineers Bring Processes of Nature to Design,” *The New York Times*, Jan. 2013, http://www.nytimes.com/, Accessed Jan. 2015.

116. “Altair Optistruct: Optimization Driven Structural Analysis,” *Altair Hyperworks*, http://www.altairhyperworks.com/, Accessed Jan. 2015.

117. G. Schuhmacher, “Optimizing Aircraft Structures,” *Concept to Reality*, Winter 2006.

118. “New IBM SyNAPSE Chip Could Open Era of Vast Neural Networks,” *IBM*, Aug. 2014, http://www.ibm.com/, Accessed Feb. 2015.

119. “Brain Power,” *IBM*, http://research.ibm.com/, Accessed Feb. 2015.

120. Johnny Madsen/YouTube, “Kalundborg Symbiosis,” *YouTube*, Sep. 2011, https://www.youtube.com, Accessed Feb. 2015.

121. “Kalundborg Symbiosis,” *Kalundborg Symbiosis Institute*, http://www.symbiosis.dk/en, Accessed Aug. 2012.

122. “About Eco-Machines,” *John Todd Ecological Design*, http://toddecological.com/, Accessed Feb. 2015.

123. “Ethel M. Chocolates Industrial Eco-Machine™ Henderson, Nevada,” *John Todd Ecological Design*, http://toddecological.com/, Accessed Feb. 2015.

IMAGE COPYRIGHTS

Cover and Back Cover

Images courtesy of NASA Goddard Space Flight Center/Flickr.

Introduction

Honeybee photo copyright Umberto Salvagnin/Flickr.

Coral reef photo copyright USFWS Pacific Region/Flickr.

Carbon

Cover photo copyright Stanley Sagov/Flickr.

Strategy photo copyright Steve Jurvetson/Flickr.

Blue Planet photo copyright Washington State Department of Transportation/Flickr.

Converge Polyols photo copyright Novomer/Flickr.

Solar Fuels copyright alonzo petrovich/Flickr.

Water

Cover photo copyright Heather/Flickr.

Strategy photo copyright Manuel M. Ramos/Flickr.

Aquaporin Inside photo copyright WaterWorld.

Seawater Greenhouse photo copyright Seawater Greenhouse.

Termite Humidity Sponge courtesy of Scott Turner.

Materials

Cover photo copyright Frank Starmer/Flickr.

Strategy photo copyright kqedquest/Flickr.

Sto Coat Lotusan photo copyright StoCorp.

Sharklet photo copyright Sharklet Technologies.

Mushroom Materials photo copyright mycobond/Flickr.

Biocement Bricks photo copyright bioMASON.

Deformable Glass photo copyright Andreina Schoeberlein/ Flickr.

Modern Meadow Leather photo copyright Cinnamon Cooper/Flickr.

Mussel Adhesive photo copyright Brocken Inaglory/ Wikimedia.

SLIPS Technologies photo copyright SLIPS Technologies

Superwicking Materials photo copyright titanium22/Flickr.

Energy Conversion & Storage

Cover photo copyright Drew Bandy/Flickr.

Strategy photo copyright Razvan Marescu/Flickr.

bioWAVE photo copyright BioPower Systems.

µMist Platform Technology photo copyright robin 24/ Wikimedia.

Pilus Cell photo copyright Pacific Northwest National Laboratory/Flickr.

Optics & Photonics

Cover photo copyright HorsePunchKid/Flickr.

Strategy photo copyright Macroscopic Solutions/Flickr.

Anti-reflective photo copyright Wei-Lun Min.

IRLens photos courtesy NASA and Roger Johnson.

IR Light sensor photo copyright e^{3000}/Flickr.

Thermoregulation

Cover photo copyright smshubert6/Flickr.

Strategy photo copyright darronb/Flickr.

Hydris photo copyright Nova Laboratories.

Unilever photo copyright nickharris1/Flickr.

Injection molding photo copyright slobirdr/Flickr.

Fluid Dynamics

Cover photo copyright NASA Goddard Space Flight Center/Flickr.

Strategy photo copyright michiexile/Flickr.

Lily Impeller photo copyright PAX Scientific.

Tubercle Technology photo copyright WhalePower.

Wind farm photo copyright John Dabiri.

Data & Computing

Cover photo copyright Zeiss Microscopy/Flickr.

Strategy photo copyright Zeiss Microscopy/Flickr.

Energy management photo copyright Encycle.

Optistruct photo copyright Altair Engineering/Aarhus School of Architecture.

IBM SyNAPSE photo copyright IBM Research/Flickr.

Systems

Cover photo copyright NASA Goddard Space Flight Center/Flickr.

Strategy photo copyright Kim Seng/Flickr.

Eco-Machine photo copyright John Todd Ecological Design.

Kalundborg photo copyright Kalundborg Symbiosis.

Phoebe photo copyright Graham Ballantyne/Flickr.


"...life on Earth is more like a verb.
It repairs, maintains, re-creates, and outdoes itself."
Lynn Margulis & Dorion Sagan, 1995
What is Life?
TERRAPIN
BRIGHT GREEN
641 SIXTH AVENUE
NEW YORK NY 10011
+1.646.460.8400
2105 O STREET NW
WASHINGTON DC 20037
+1.202.470.0401
TERRAPINBRIGHTGREEN.COM
BIOMIMICRY@TERRAPINBG.COM
@TERRAPINBG | @NY_BIOMIMICRY | #TAPNATURE